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# Project Report on an Oasis-region
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Research Team for the Oasis Project

Research Institute for Humanity and Nature

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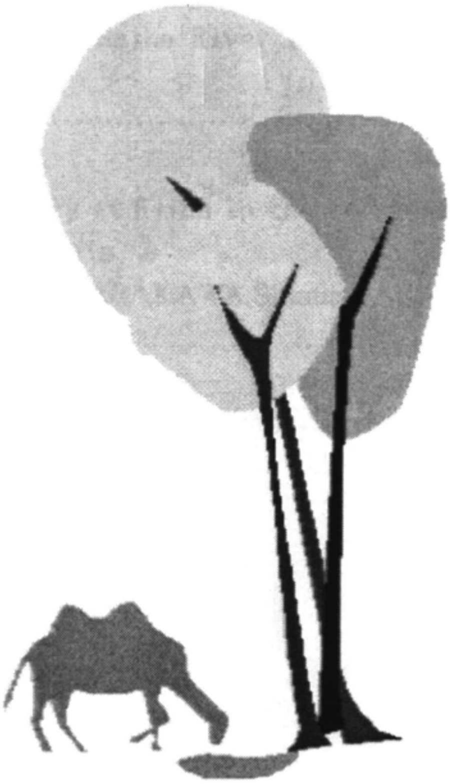

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**Research Institute for Humanity and Nature**

# Contents

# Preface

NAKAWO, Masayoshi
*Research Institute for Humanity and Nature*

In October, 2005, Pre-Symposium for the RIHN Inaugural International Symposium, scheduled in November, 2006, was taken place, and the Oasis Project took part in the pre-symposium in 18 and 19 of October. This volume includes papers presented in the Oasis Project Session and the Inter-Project Plenary Session. Professor Cheng Guodong of the Gansu Branch of the Chinese Academy of Science intended to participate to present a paper to introduce a Chinese challenge to overcome the water scarcity in the Heihe River Basin. However, he had to cancel the participation, because of his engagement in the Reviewing Taskforce of Academic Degree Committee of the State Council, People's Republic of China. We include in this volume, therefore, a paper prepared by Wang Genxu, who stayed with us for several months as an invited researcher in 2004. I hope that his paper would compensate the absence of Professor Cheng.

More than four years period has passed since we launched the Oasis Project, and it has yielded several outcomes. Before the pre-symposium, we have organized two international symposia held both in China: one in Beijing and the other in Lhasa. The content of the former meeting, "China-Japan Symposium on Ecological Migration" held in Beijing in July 2004, has been published in Japanese by the Showado Publishing Company in last July as a second volume of the Chikyuken-sousho (The RIHN Series) entitled "Ecological Migration". This book was translated into Chinese, and published in last September by the Inner-Mongolia University Publisher. It is now under translation into English, and we hope to have it published in English in a year or so. I would conclude this preface by describing the Introduction of the book below.

*Exposure to environmental issues has resulted in an increased awareness among many people who instinctively tend to support initiatives that address environmental problems. However, in order to determine whether these measures are likely to be truly effective, it is essential that they be verified carefully and scientifically. (Several sentences omitted) This book academically explores the various measures proposed to solve environmental problems by implementing the concept of "ecological migration."*

# Climate change and water use in the Heihe River Basin : information from historical documents Part I :Han Period

MORIYA, Kazuki
*Research Institute for Humanity and Nature*

Early Imperial Chinese dynasties based on the Yellow River basin of now Shaanxi and Henan province where were relatively wet and warm. On the end of the 2nd century B.C., Han dynasty first advanced into the arid Edsen-gol region. Until then, Edsen-gol region had been under the rule of a Nomadic state, Xiongnu. Xiongnu often struggled with Imperial Chinese dynasties like Qing and Han. In 200 B.C., Xiongnu won a victory over Han, and Han had to adopt an appeasement policy about diplomatic relations with Xiongnu. It was so humiliating to Han court.

After Wudi 武帝 of Han started to govern by himself, he removed the appeasement policy, and the Han army and diplomatic missions were sent over the frontier wall. The war between Han and Xiongnu was reopened. In 121 B.C., Hunye-wang 渾邪王 surrendered to Han. Therefore, Han advanced into the Hexi corridor and established Hexi four commandery 河西四郡, Wuwei 武威, Zhangye 張掖, Jiuquan 酒泉, Dunhuang 敦煌, that were directly controlled by Han government . It was an epoch-making event that an Imperial Chinese dynasty went into ruling arid area.

While Han government established a direct controlled territory, they built large defense facilities on the Hexi corridor. The frontier wall and watch towers are ranging from west of Dunhuang Yumenguan-gate 玉門関 (an oasis near the end of Sulu River 疏勒河) to Juyan 居延 area (an oasis near the end of Ruoshui 弱水). Ruins estimated Han watch towers stretch toward east. Someone thinks that the line of these watch towers may extend to Ordos.

Wooden slips were unearthed from these watch towers and ruins of their upper sections. We call these wooden slips unearthed on Juyan area Juyan wooden slips of Han Dynasty 居延漢簡 (Juyan Hanjian). The Scientific Expedition to the North-West Provinces of China under the leadership of Dr. Sven Hedin (The Sino-Swedish Expedition) investigated Edsen-gol region in the 1930's, and they found over one million wooden slips. After then, Chinese scholar excavated Juyan area in the 1970's and 2000's. Two million wooden slips are classified and published until now.

We can divide the excavated area of Juyan into two oasis area. One is the area between Ikhen-gol river basin and Juyan Lake. This oasis area is surrounded by frontier walls and watch towers. Other one is the oasis, now Dingxin 鼎新 and Shuangcheng 双城. Commandant-office 都尉府, which is under the direct control of commandery, was established in each oasis.

We can find out an administrative system of Hexi corridor in Han dynasty from Juyan wooden slips (Fig.1). Because wooden slips were unearthed from defense facilities like watch towers, most of records written with wooden slips are about defense system. But there is little information about administrative system, so the exact place of Juyan district is not confirmed until now.

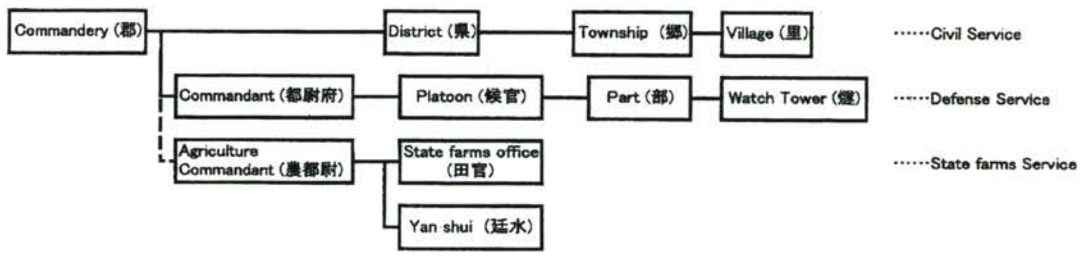


**Fig. 1**[1]

State farms section existed besides defense and administrative section. It had jurisdiction over state farm. On wooden slips, we can find words like "Tianzu 田卒", "Tianguan 田官". Tianzu means state farms soldier, Tianguan (state farms office) controlled them. "Hanshu 漢書 (The History of Han Dynasty)" says that large scale farming development policy, called "daitianfa 代田法", was put into effect. The word "daitiancang 代田倉 (granary for daitianfa)" is found in records of wooden slips unearthed from A10, and we can know that a farming development based on daitianfa was carried out in Juyan area. From A10, a plow also was unearthed (Fig.2), so it is clear that this area was used as cultivated land. But now, it is said that this A10 area is covered with sand drifts very

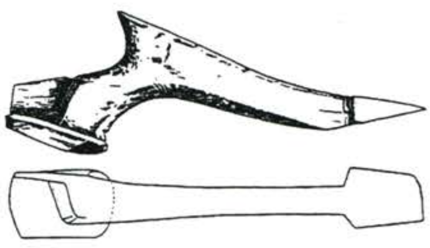

Fig.2

[1] As Qiu Xigui 裘錫圭 ("Management of government-owned farmlands in Qin-Han period seen from excavated written documents 從出土文字資料看秦和両漢時代官有農田的経営" *Integrated studies of Chinese archaeology and historiography* 中国考古学与歴史学之整合研究, 1997.7, Taipei) mentions, Agriculture Comandant might belong to Chamberlain for the national treasury 大司農.

thickly, so it is difficult to find out a trace of cultivating of Han period.

However, we can see farming ruins with pottery of Han and Xixia (or Yuan) period in the same place. Especially, southeast of L□cheng 緑城 is set up by remains of channels, so we can consider this area was large-scale cultivated land. In this "L□cheng Area", there are a lot of tombs of Wei-Jin period; moreover tomb of Bronze Age was also excavated, so it is obvious that human beings settled down in this area for long time. The theory of Li Bingcheng 李并成 who suggests Juyan district was placed at L□cheng is not supported by many scholars[2], but when the target of consideration is expanded to "L□cheng Area", it is necessary to reexamine his theory. But there is not enough data for us to discuss about this problem, because neither Stein nor Bergmann reached to "L□cheng Area". To solve this outstanding problem, it is very important to clear the age when each irrigation ditch and cultivated land started to use.

It is notable that records on Tianguan are only found in Wudi, Zhaodi 昭帝, and Xuandi 宣帝 periods. In an early period of Juyan development, state farms soldier cultivated farmlands, and soon, common people took a place of state farms soldier. Therefore, administrative section also took a place of state farms office. It was continued at least to Wei-Jin period when power of central government decreased by war.

Besides Tianzu, a word "Zhiquzu 治渠卒 (millrace maintenance soldier)" is found in wooden slips. They maintained irrigation ditches under "Yanshui 延水". They estimate that state farm area were on around K710 and A8 (Jiaqu Houguan 甲渠候官). The name Jiaqu Houguan came from an irrigation ditch that was conducted water from Ikhen-gol. Tianguan controlled subordinates named "Diyizhang 第一長 (First manager)", "Dierzhang 第二長 (Second manager)".

> "The forth manager, Anqin 安親 pressed a total of 27143 labors into farming during 224days, from January to August. Suppose 121 labors cultivate per day. 39 labors should be left over. They cultivated a total of 41qing 44mu 124pu. Suppose a labor cultivates 34mu. 30mu 124pu land should be left over. The crop is 2913shi 1dou 1sheng. Suppose a labor harvest 24shi. 9shi should be left over."
> (72.EJC-1)[3]

The numbers of managers meant the numbers of irrigation ditches. This fact is evidence that farmlands were organized with each irrigation ditch.

Not only state farms soldiers but also common people cultivated farmlands. Most

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2 Li Bingcheng, "New consideration on Juyan district of Han dynasty 漢居延県城新考" *Kaogu* 考古 1998-5 pp.82-85.

3 The picture of this wooden slip is not published so far. Only letters are published on *Precise interpretations of new Juyan wooden slips of Han Dynasty* 居延新簡釈粋, 1988.1, Lanzhou, p.87.

of them were forcibly immigrated from Yellow river basin. "Hanshu" mentions "extremely poor peoples of Guandong 関東, persons who retaliated in inadequate way, atrocious persons" as forcibly immigrated peoples. "Extremely poor peoples of Guandong" is thought that "residents of Yellow river basin who suffered damage from the flood caused by destructive development in Ordos".

The chief of Juyan district was called "Juyan magistrate (Juyan ling 令)". In the Han era, if a district controlled over million households, a chief of the district was called "ling". So we can say many immigrants from Yellow river basin lived in Juyan district. After middle period of East Han, wooden slips of Juyan decreased sharply. But it only means frontier walls and watch tower lost there function as defense facilities. Descendants of immigrants from Yellow river basin kept on farming in Juyan area.

# Climate and Irrigation Systems of the Heihe River Basin in the Qing Dynasty

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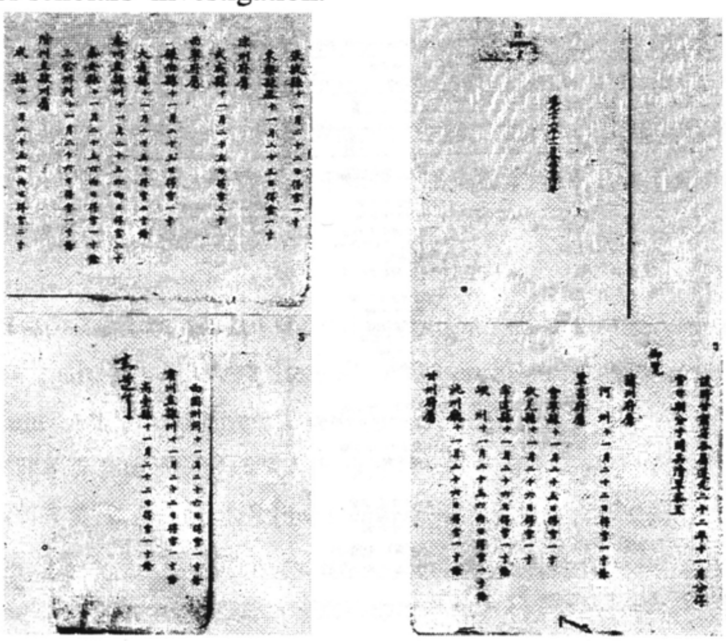
KICENGGE (*JSPS Postdoctoral Foreign Fellow,RIHN)*

## Introduction

There is no doubt that most of written historical materials about Heihe river basin during the Imperial China were recorded in the Qing dynasty. Because of their bureaucratic and frontier regulation system, remains of historical items are mostly about midstream of the Heihe river. So, when we talk about residents' life and environment of the Heihe river basin during the Qing dynasty, our description must concentrate on Ganzhou (甘州) and Suzhou (肅州) area. In the next report, if we will occasionally write about Edsen Toryud banner, it will be expressed in an ethnic relationship context. Anyway, this paper is an interim report that we got from the Qing archives.

## 1. The Qing Palace Memorial Archives on environmental information

When we study climate during the Qing dynasty (1644-1911A.D.), we can mainly read archives of the Qing court and government. At present, they are collected in the First Historical Archives of China (Beijing) and the National Palace Museum (Taipei), and are offered for scholars' investigation.



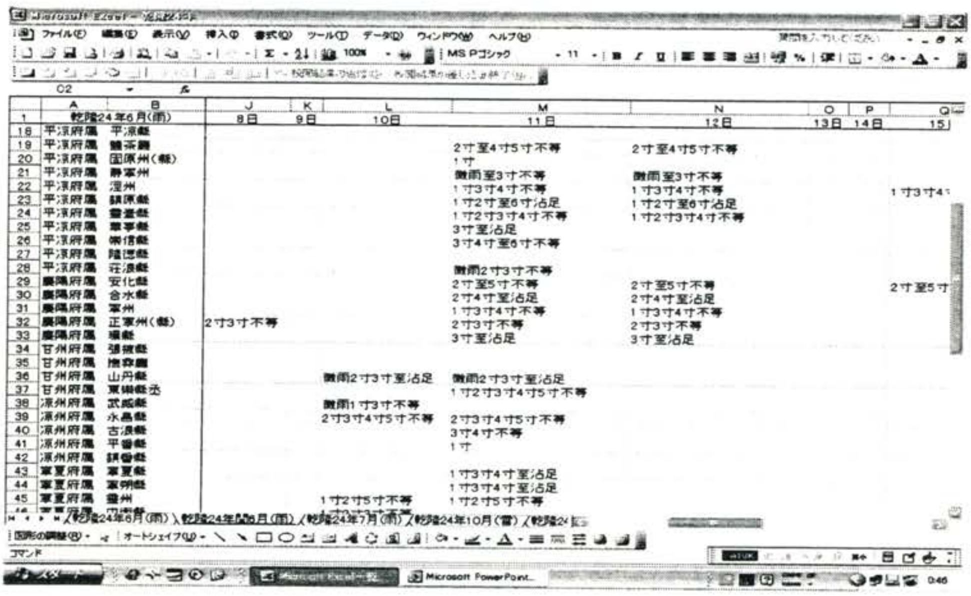
The Qing Palace Memorial Archives on Gansu environmental information

Especially from Kangxi period (康熙 1662-1722A.D.), governors-generals (zongdu 總督) and governors (shunfu 巡撫) were required to make monthly reports to the Emperor on precipitation, abnormal weather, crop's fiars and condition of residents under their jurisdiction. Qianlong emperor (乾隆皇帝 1735-96 reigned) had systematized their report duties.

Like photos, archives include daily data of the amount of rain and snow from 1707 to 1911, for more than 200 years. Governors had reported when and how long and how many rain or snow or hail had fallen.

Palace memorial archives on Gansu weather information are edited and provided to us by the First Historical Archives of China. Senders of documents are governor-general of Shaanxi-Gansu (陝甘總督), governor of Gansu (甘肅巡撫), Gansu provincial administration commissioner (甘肅布政使) and so on. They reported precipitation in Gansu province mostly, but they little referred to temperature. When they wrote about general climate in Gansu, they repeated a stock phrase "Here is cold and arid." Their greatest concern was a suitable time and amount of precipitation, wasn't that temperature was high or low. Snow falls in winter and spring were considered as good omens. They worried about shortage of rain fall, because it may lead to a poor harvest. Like floods and flash floods, disasters caused from heavy rains were reported in detail, we can know number of collapsed houses and extent of damaged fields.

And we made Excel charts from these archives. Using these data as one of important elements, our colleagues are trying to reconstruct the past environment in Gansu province.



Using for calculation and analysis, we are converting chinese representation into numeral values now. So, after few month, we can get a results of the analysis.

## 2. Method of Observing Precipitation

Until quite recently, nobody knows how government officials observed precipitation. They only wrote how long depth rainwater penetrated into soil. There is no information about a method of observing precipitation in Han Chinese archives. But Manchurian archives teach us that they dug up the soil, and measured depth of penetrating rainwater.

"At Tongzhou, it started a heavy rain in both 19th and 20th, and additional heavy rain came at midnight of 22nd, followed by a series of fair rains. We dug up the soil. The soil was found wet down to the depth of 1 Chinese inch and so."

3550 經筵講官賴都等奏報熏談祈雨情形折(康熙六十年四月二十三日)

經筵講官禮部尚書賴都等謹奏,為奏聞事。

臣等欽奉諭旨:十九日熏壇,二十日始至二十二日三天祈雨,十九日未時,雷鳴落細雨,酉時電閃復落一陣雨,二十日陰,從二十二日子時雨瀟瀟,至寅時雨歇,巳時復落一陣雨。臣部遣員外郎孫鴻至通州,遣員外郎,覺羅充武至沙河,遣員外郎希德至共給城,遣員外郎尚崇壇至黄村查看。二十二日午時歸來。據孫鴻告稱:詢問通州農夫,通州地方,十九,二十日,驟降雨一陣,二十二日夜半,降大雨一次,復降一陣細雨云云,返回時,仍降小雨,掘土觀之,有一寸餘;據覺羅充武告稱:詢問沙河地方農夫,據稱:二十一日雞鳴時,雨瀟瀟一陣云云,掘土觀之,有一寸濕土;據希德申告稱:到達共給城,詢問黎民,據稱二十,二十一日淫雨霏霏,今日雞鳴時雨瀟瀟云云,我往返之間,落雨二次,各處掘看,濕有一、二寸不等;據尚崇告稱:詢問黄村黎民、二十、二十一日、降落小細雨云云、我出城即雨瀟瀟, 至草橋,雨止,由黄村此方各處掘土觀看,足有一寸濕。四面得雨,京城又從來時起降雨瀟瀟,申時止,仍陰天間斷降雨,雨止天晴虹現為此謹具奏聞。

經筵講官禮部尚書賴都,經筵講官尚書蔡升元、右侍郎景日昣

硃批:口外冬、春雪大、剛剛得雨、糧麥拔節好、今春、夏正旱、山東、河南、直隸地方尚未奏報落雨、爾等所報地方雨未沾足, 再祈雨。(中國第一歷史檔案館編 1996『康熙朝滿文硃批奏摺全譯』中國社會科學出版社,p. 1472.)

"(In Rehe region) A heavy rain started accompanied with thunderstorm with lightning in midnight of 12th. We dug out the soil. The percolation depth of rain water was found to be equivalent with 5 to 6 fingers with spatial variation."

3556 禮部尚書賴都等奏報祈雨得雨情形折,康熙六十年六月十三日

禮部尚書賴都等謹奏:欽遵上諭,六月初十日始祈雨,十一日未時一、二刻降微雨, 本時正一刻止;十二日亥時二刻電閃雷鳴降大雨,本時正一刻未止。掘地觀之,濕有五、六指深不等。為此謹具奏聞。

經筵講官禮部尚書臣賴都、經筵講官尚書加一級臣蔡升元、左侍郎革職留任贖罪效力臣王思世、右侍郎革職留任贖罪效力臣羅詹、右侍郎臣景日昣。

硃批:今毋須報雨、熱河地方恐過分、以致憂患。(中國第一歷史檔案館編 1996『康熙朝滿文硃批奏摺全譯』中國社會科學出版社,p. 1475.)

Here we can think of one question. When there is a certain depth of penetrating rainwater, how much did rain fall? It may depend on a nature of the Gansu soil. But we don't have an information to consider about it now.

## 3. Comparison with Dunde ice core analyses

When I prepare this paper, I read through the over hundred year archives. And I tried to compare data of archives with data of Dunde ice core analyses. Annually-averaged oxygen isotope data from the Dunde ice core can be indexes of temperature at Dunde ice cap. But, as I mentioned, governors of Gansu didn't record how they felt temperature, so this time we should abandon this examination.

About precipitation, we are editing Excel chart data at present, so we must wait few month to compare with Dunde accumulation data calculated by Dr. Sakai.

Archives on farming show us how a harvest was in each year. In Qianlong 28th (1763), 45th (1780) and 55th (1790), they got bad harvests. Using these informations, we may be able to compare data from archives with data from ice core analyses.

After Jiaqing era, monthly reports on precipitation became routine. Documents attached to reports decreased supplementary information. It is painful that we read archives after Jiaqing era.

## 4. Hedong and Hexi

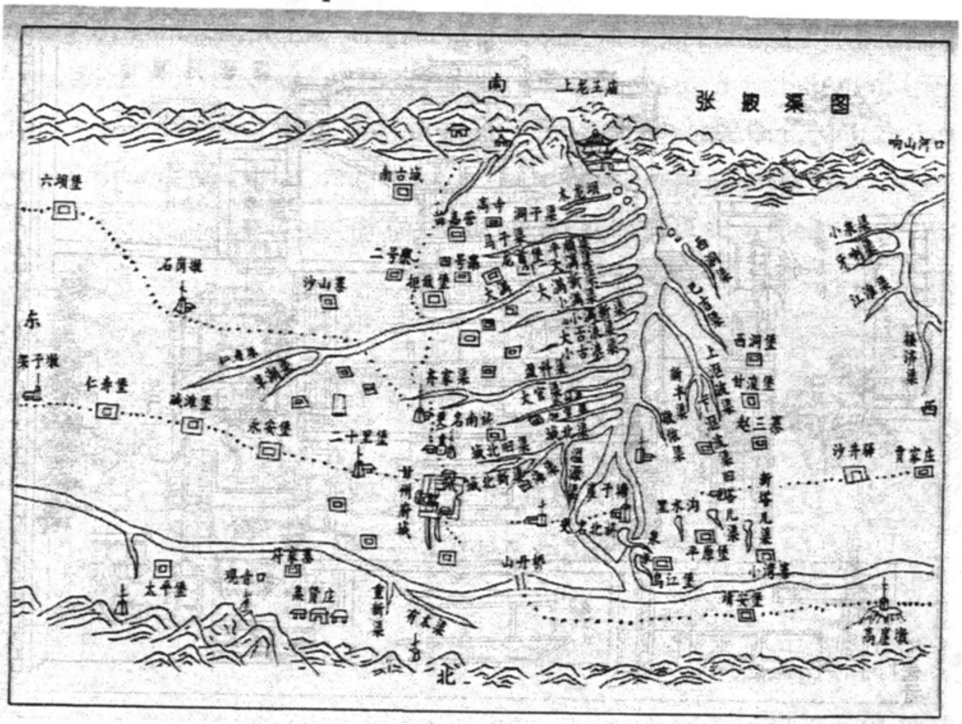
Gansu province is divided into three regions, Hedong(河東) , Hexi(河西) and Anxi(安西). Hedong is the east side of Yellow River. It consists of Lanzhou prefecture(蘭州府), Pingliang prefecture(平涼府), Qingyang prefecture(慶陽府), Gongchang prefecture(鞏昌府), Qinzhou department(秦州), Jinzhou department(涇州), Jiezhou department(階州). Hexi is the west side of Yellow River. It consists of Liangzhou prefecture(涼州府), Ganzhou prefecture(甘州府), Suzhou independent department(直隸肅州). Ninxia prefecture(寧夏府) and Xining prefecture(西寧府) was on the boundary between Hedong and Hexi.

Precipitation and other information were reported about Hexi and Hedong always separately. Trends of precipitation in each region are different. Especially in Hedong, extremely high and low precipitations could lead to droughts and floods remarkably. Besides, irrigation ditches were insufficiently equipped in Hedong. The region could suffer heavy damage from disaster. Because Qilian Mountains, that have many glaciers and large forest, is the hinterland of Hexi, the region can be supplied water stably. Governors thought that enough supply of water must lead to a good harvest.

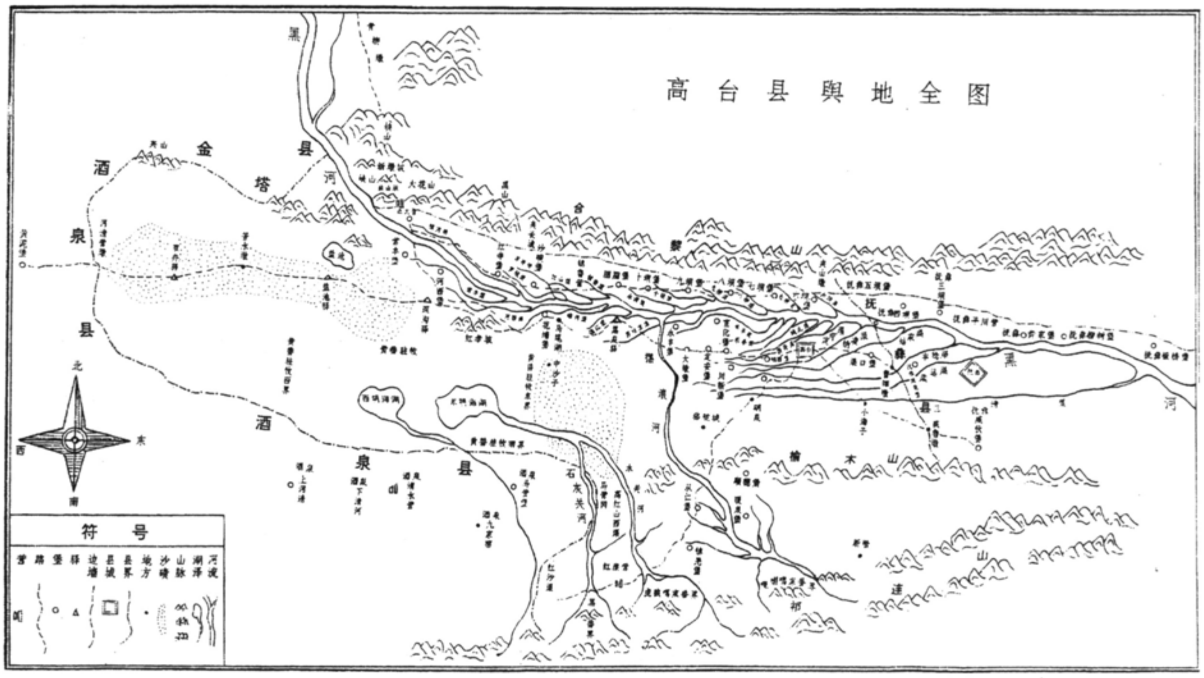
5. Irrigation system in Heihe River Basin

Because of well-established irrigation system, Hexi region became a stable farmland. When we study the historical evolution of the inter-relation between natural and social systems in the Heihe river basin, irrigation system is one of most important element. I will examine the irrigation system and the rule to manage local association for water use.

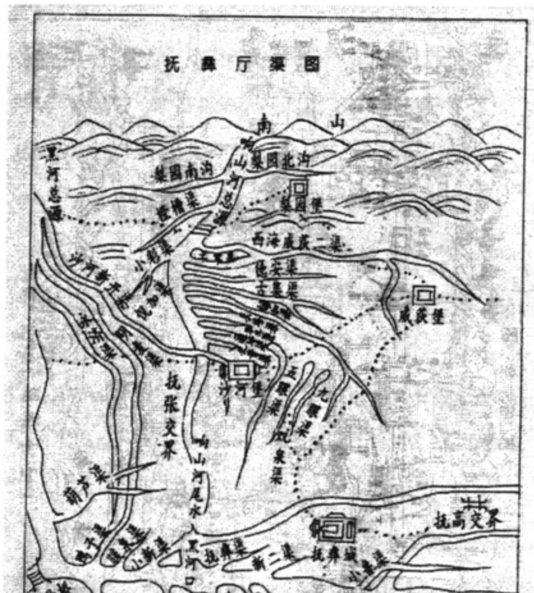
In Hexi region, they had made irrigation ditch systems against aridity and supplied water for arid lands. Irrigation system had been managed in this area all along historical period. And now they also use same irrigation ditch, however, irrigation technology have evolved. When we see Qing maps of regional irrigation ditches, we can find same names with exist ditches on same places.



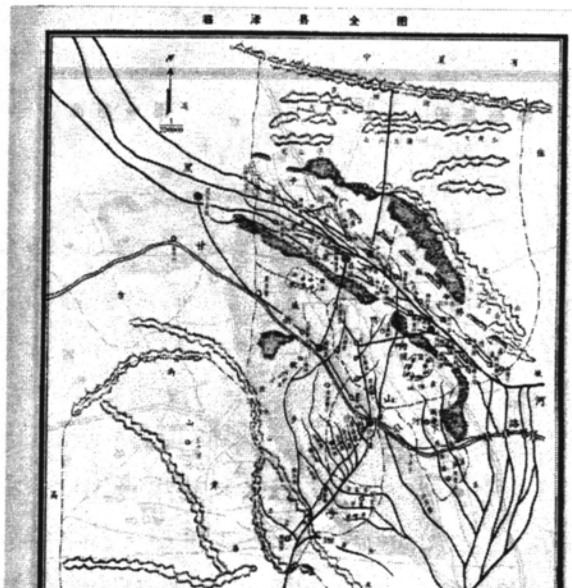

Irrigation map of Zhangye district




Irrigation map of Gaotai district




Irrigation map of Fuyi subprefecture



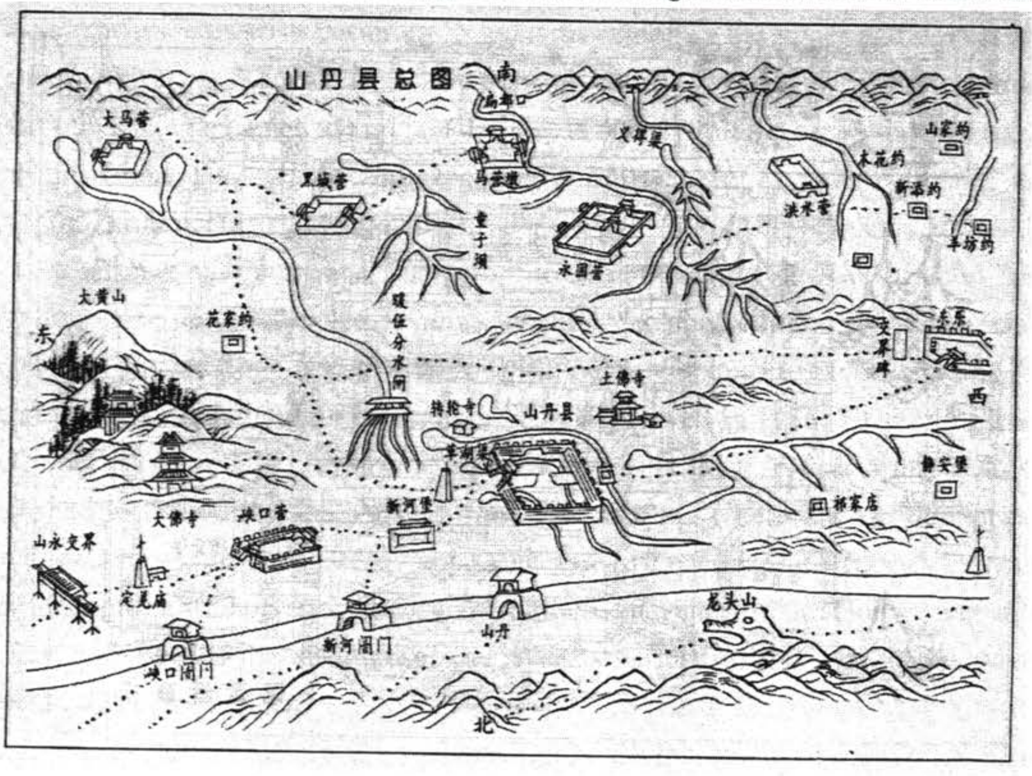
Irrigation map of Linze district

6. Community Compact for Irrigation rights

In the Heihe river basin, Shandan district (山丹縣) has a detailed record of community compact for irrigation rights. It was recorded in the Gazetteer of Shandan district of Daoguang period (道光山丹縣志).

In the Hexi corridor, irrigation water was conducted from rivers or fountains. If necessary, qanats were also excavated. And there were five major irrigation ditch systems in Shandan. Caohu-ditch (草湖渠), Nuanquan-ditch (暖泉渠), Dongzhong-qu (東中渠), Tongzi-ditch (童子渠), Muhua-ditch (慕化渠), these ditch systems were managed during Qingming (清明) and the winter solstice (冬至), and were conducted water six times. First two times are for preparing planting (安種水). Second two times are for growing crops (苗水). Last two times are for pouring water into the soil and preparing next year's farming (冬水). Time schedules and amounts of irrigation water for each field were prescribed by community compacts according to the extent of farmlands.

For managing irrigation systems, irrigation manager were appointed by district office and local worthies. But residents were not always satisfied with distribution of irrigation water. They were dragged into the struggles for water use. Ganzhou department magistrate and Shandan district magistrate act as mediators. And their judgments were often engraved on monuments, and gave residents the guidelines for their water use.




Irrigation map of Shandan district

## Conclusion

The oases of the Heihe river basin, especially in the midstream, were very stable farmlands. Their stabilities were guaranteed by glaciers on the Qilian mountains and well-established irrigation system.

But our investigation doesn't find out remarkable environmental changes of there at present. Dendrochronological analysis by Prof. Zhang Qibing and Prof. Kobayashi will provide us data of event years. In the next step of our study, we shall inspect written records of event years, and describe reactions of residents and local governments in those years. And we hope historical study, ice core analysis and dendrochronological analysis can verify each data integratedly.

# Environmental Change and Human Activity at Ejina in the 14th century turned out through written historical materials

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ARAKAWA, Shintaro *(Tokyo University of Foreign Studies )*
SATO, Takayasu *(Osaka University)*
FRUMATSU, Takashi *(Kyoto Uniersity)*
IGURO, Shinobu *(Ohtani university)*

**Introduction**

Recently, a serious problem occurs in the Heihe 黒河 river basin. Heihe river water does not flow to the downstream, and two lakes in the lowest reaches of the river have disappeared. The shortage of water in the Heihe river basin has an important influence on the life of people who live in this region. The factor that brings the water shortage is various, and is combined. A decrease in precipitation according to global warming and progress of dryness, excessive water usage in the agricultural region in the middle reaches, excessive pasturing in nomadic region in the upper and downstream of the Heihe river, and so on. It is not easy to clarify the causal relation because the environmental change and the human activity is closely related each other. To solve this problem, Chinese government is executing various measures now. However, another new problem is occurring along with it.

A great environmental change occurred in the Ejina 額濟納 oasis in the past. One huge lake that was called Juyanze 居延澤 disappeared, and two lakes, Gashoon nur 嘎順淖兒 and Sogo nur 蘇泊淖兒 appeared newly before. **Plate 1.** is The Map of China and the Barbarian Lands (*Huayitu* 華夷圖) carved in 1136. This map shows that there was only one lake, Juyanze at Ejina. **Plate 2.** is from *Nouvel Atlas de la Chine*, published in France in 1753. At that time, Gashoon nur (indicated as "Souhouc Nor") and Sogo (Sobo) nur have already appeared, and Juyanze lake has not exist any longer. This phenomenon happened because the amount of water of the Heihe river changed greatly, and the flowing direction of the river came near to the west. Then, when and why did this event happen?

To clarify this problem, we are advancing the decipherment of the written historical materials that has been left now. The main one is the documents written in Chinese discovered from Khara Khoto 黒城 in 1983, which were recorded in Yuan 元 era, published in 1991, and are called Khara Khoto Document. Besides this, we use recorded information to the history books and the old maps, those were chiefly made in China. In addition, we refer to acquired data from the archeological investigation, the analysis of the satellite photograph, and the investigation of the lake sediments.

## 1. Agriculture and water use at Ejina in the age of Xixia and Yuan

There is some old maps which were drawn the situation of Ejina. **Plate 3.** is the map of the lower Heihe river and Juyanze lake carried by the local gazetteers; *Ganzhenzhi* 甘鎮志 and *Suzhenzhi* 粛鎮志, completed in 1657 of Qing 清 era. But this map is drawing the situation before the 14th century. According to this, it turns out that Khara Khoto (Yijinai castle 亦集乃城) was surrounded by branched Heihe river and the river which flowed together in the northeast were flowing into Juyanze lake (Yijinai sea). **Plate 4.** is a satellite photograph which took present Khara Khoto. The relation between the paleo-channnel of Heihe river and Khara Khoto are completely in agreement with the situation shown in **Plate 3.** According to the investigation of the lake sediments, it turned out that the large quantities of water flowed into Sogo nor, and its area had expanded rapidly in the 12th century.

When this map was drawn first, this region was under the rule of Xixia 西夏 and Yuan Dynasty. Around Khara Khoto and Lucheng 緑城, innumerable irrigation canal was pulled from Heihe river, and vast farming ground extended. It turns out that the many were used from the age of Xixia to Yuan by the investigation.

There are a lot of uncertain points of the situation in the Xixia era. According to historical materials, the peoples of Xixia engaged in irrigation agriculture and stock raising by using the thaw water of Qilian 祁連 Mountains in this region. **Plate 5.** is *Shengli yihai* 聖立義海, vol. 2, "The names and meanings of the mountains", excavated from Khara Khoto. This book is the encyclopedia of Xixia.

In the age of Yuan Dynasty, a central government strongly initiated immigration, and this policy was executed in the frontier region of China. Ejina was not an exception. In the age of Qubilai, it is recorded that 200-300 soldiers immigrate, and developed 500 hectares or more newly in cooperation with the vicinity resident. After that, when intensive agriculture, Outianfa 區田法 in Chinese, was introduced, the latest agricultural books were distributed to the whole country. The document that shows the state of execution of the intensive agriculture in this place has been excavated from Khara Khoto, with the fragment of an agricultural book's illustration. See **Plate 6.**

Among the main irrigation canals around Khara Khoto, the name of eight places is recorded in the Khara Khoto document. To our regret, the accurate position of them is uncertain now.

In Ejina, under the inspection and the guidance of a senior organization, undersecretaries (tongzhi 同知) of the provincial government (zongguanfu 総管府) had jurisdiction over the irrigation business with subordinates of a special department (hequsi 河渠司), and they presided over the distribution of the agricultural water. Some points artificially modified are confirmed in the paleo-channnel of the river around Khara Khoto. They might have initiated such public works. See **Plate 4.**

The residential population of the farm village around Khara Khoto is estimated to be about 4000-5000. They were incorporated to the executive organization "she 社 (society)". In Ejina, some societies of each irrigation canals were organized, the potentate in each society was appointed to "shechang 社長 (president)", and a big authority was given. Moreover, the official position named "biaoshui 俵水 (water distributor)" was appointed. Their important duty was to distribute the water corresponding to the area of each farmland.

The method of distributing water to the farmland and the organization that manages irrigation agriculture was never changed almost in principle in the Hexi corridor 河西走廊 region from the age of Tang Dynasty. There are a lot of uncertain points of a concrete situation of the water management in Khara Khoto. However, it is thought that the same method as other regions; Dunhuang 敦煌, Zhangye 張掖 and Wuwei 武威 etc., was adopted.

Crops such as barley, wheat, millet, and gaoliang were grown in this region. See **Plate 7.** They are the most popular clops in the northwestern region of China. These farm products occupied the main part of a financial income of this place, and supported the life of the stationing army and city people. As for Marco Polo, the occupation of native people in Ejina was farming and stock raising, and nobody was engaged in the trade. It was a blessing of Heihe river water to bring the prosperity of Khara Khoto.

## 2. Shortage of water and change of life environment in the 14th century

The climate of Ejina was extremely severe in those days. The strong seasonal wind from the northwest always blew a large amount of quicksand, and buried the irrigation canal and the farmland. There were a lot of salinities and gravel in the soil, and the cultivation was quite difficult. The drought and the damage by insects that happens frequently have ruined a harvest.

The continuing calamity brought the great famine and war disturbances in various parts of China. The drought and the famine often happened in Ejina when entering the 14th century. It was not easy to rebuild the impoverished farm village though the government tried to relieve the people from the disaster. When a large-scale military campaign happened, the food that had to be supplied to soldiers and horses could not help relying on another region, Zhangye and Jiuquan 酒泉. **Plate 8.** is the document concerning military food written in 1300 excavated from Khara Khoto. Moreover, the appeal of a local government official who seeks a transfer is recorded in the document of the age because of the hard living in Khara Khoto at the last years of Xixia. Circumstances in Khara Khoto were not easy at all.

In the middle of the 14th century, the transportation and supply of food from another region was stopped in Khara Khoto, and the stockpile has almost become empty. The bill that circulated on a nationwide scale became the wastepaper in an extreme inflation. Prices were calculated based on the amount of wheat. **Plate 9.** is one of the bill printed in Yuan era excavated from Khara Khoto.

The serious change happened when Khara Khoto fell into a critical situation. According to the local gazetteers, in the 14th century, Juyanze which had been one vast lake was "divided into three small lakes", and "these three lakes were so small that they were not equal to the small lake in the China mainland." It is not clear that these three lakes are equivalent to the present lakes, such as Gashoon nur or Sugo nur. However, it is clear that the amount of water of Heihe river and Juyanze lake had been decreasing sharply at that time. **Plate 10.** is the Map of the Nine Frontiers of Imperial Ming (*Huang Ming jiu bian tu* 皇明九邊圖) and The Research on Rule of Frontier (*Bian zheng kao* 邊政考), printed or drawn in the middle of the 16th century. According to them, Khara Khoto is surrounded by Heihe river and three small lakes.

It is thought that these problems are closely related to the climate change that happend globally at that time. What causal relation exists between a lot of disasters that attacked Khara Khoto and the shift to the Little Ice Age? It is a problem that requires the progress of a further research. However, it is necessary to have thrown a dark shadow on people's livings at that time. And it has already become impossible to support the situation in the will and the power of the government.

### 3. Abandonment of Khara Khoto castle and situation of Ejina after 15th century

The expedition army of Ming 明 battled three times in 1372, 1380, and 1384, and expelled Yuan power from Khara Khoto. However, did Ming really change Heihe river's flow, and cut off the water supply as talked to the legend in that case? Nothing is recorded in historical materials. In the southwest of the Ejina, there is a large dune that runs north and south. According to the investigation, it is said that the structure that the flow of the river was artificially dammed up exists here by two places. After the $15^{th}$ century, the reconnaissance troop was sent to the ruin of Khara Khoto several times. According to their reports, the palaces and temples that had been decorated with beautifully colored construction materials and colorful roof tiles stood like old times. The castle was abandoned after the end of the $14^{th}$ century, but was not destroyed.

On the other hand, Ejina region never fell into the desolate wilderness after the $15^{th}$ century. At the beginning of the $16^{th}$ century, it is recorded that more than 1000 Chinese people get across the desert and back to the town in suburbs of Wuwei. They lived in Ejina, and were engaged in farming and stock raising. But they rioted by some reasons, and returned to their hometown. According to the survey, there are some ruins of the farmlands and the irrigation canals used after the $15^{th}$ century around Khara Khoto. Ejina disappears from historical materials in the age of Ming Dynasty, and there are a lot of uncertain points of detailed circumstances. However, many people had existed here before the Torguut people came back to Ejina in the $18^{th}$ century.

## Conclusion

In the age of Xixia and Yuan, Heihe river flowed in the direction of Khara Khoto and was flowing into the Juyanze lake which was in the northeast of Juyan oasis. Many irrigation canals and vast farmlands were extended to the near region of Khara Khoto.

In the $14^{th}$ century, the amount of water of Heihe river and Juyanze lake decreased sharply, and the direction of the main stream of the river also changed northwardly along with it. Agriculture has declined because the climate becomes cold, and the disaster happened frequently.

The irrigation farmland was developed on a large scale also in middle reaches of the Heihe river in this age. It is not made clear whether this development related to the shortage of water in the downstream. This is a problem to be made clear from now on.

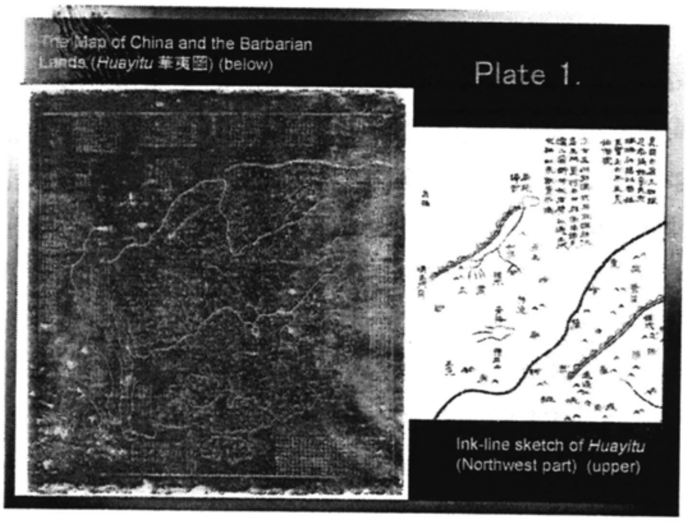
The Map of China and the Barbarian Lands (Huayitu 華夷図) (below)
Plate 1.
Ink-line sketch of Huayitu (Northwest part) (upper)


Plate 2.
Occupeé par une partie du Cobi ou Cha-mo desert sabloneux, jusqes à la Ville de Hami (eastern part) (below)
Carte Generale de la Tartarie Chinoise (western part) (upper)

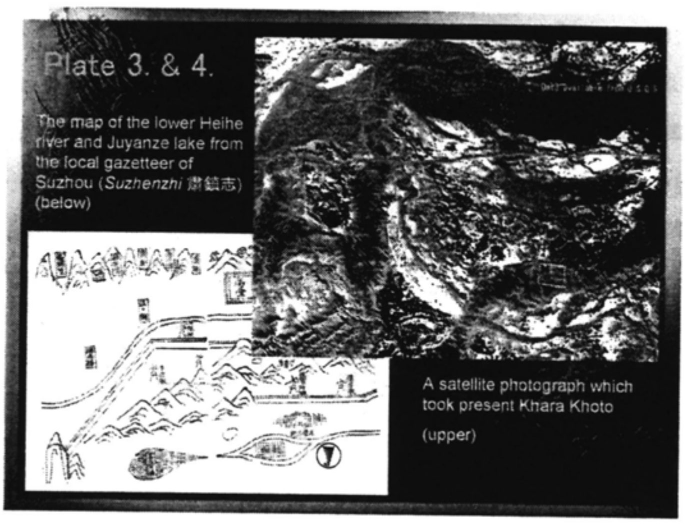
Plate 3. & 4.
The map of the lower Heihe river and Juyanze lake from the local gazetteer of Suzhou (Suzhenzhi 肅鎮志) (below)
A satellite photograph which took present Khara Khoto (upper)


Plate 5.
Shengli yihai 聖立義海, vol. 2

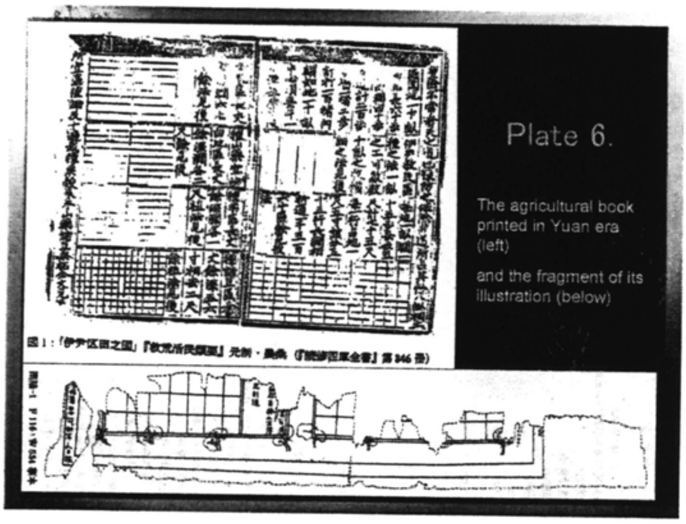
Plate 6.
The agricultural book printed in Yuan era (left)
and the fragment of its illustration (below)

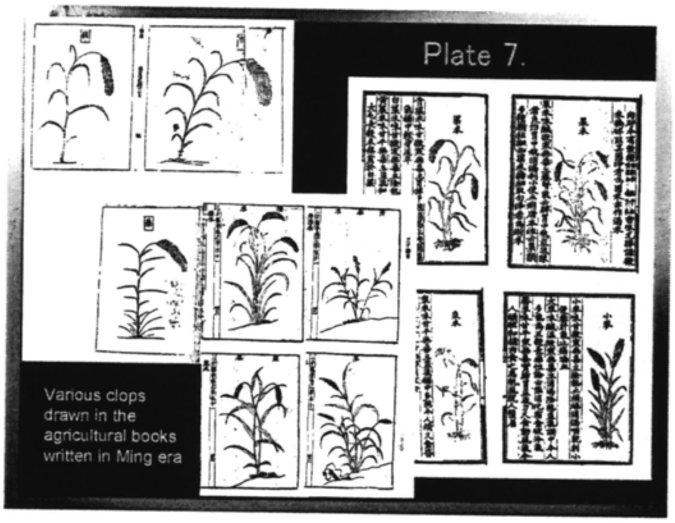
Plate 7.
Various clops drawn in the agricultural books written in Ming era

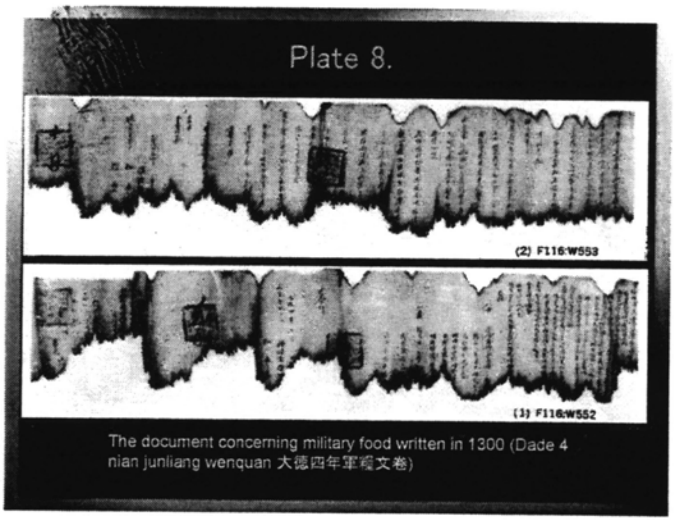
Plate 8.
(2) F116:W553
(1) F116:W552
The document concerning military food written in 1300 (Dade 4 nian junliang wenquan 大德四年軍糧文卷)

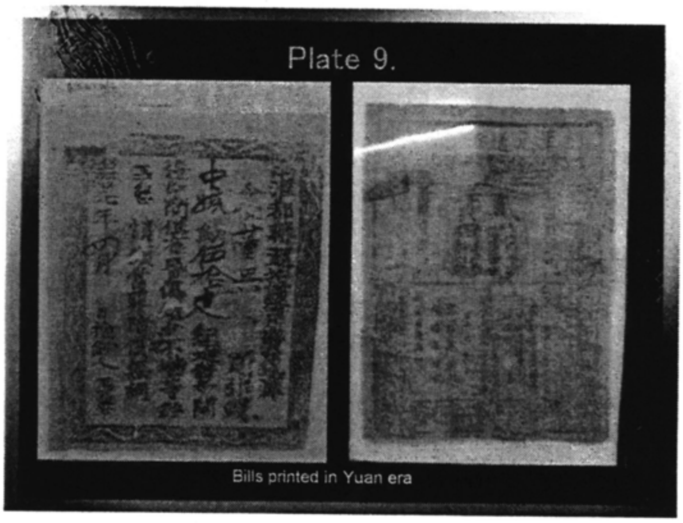
Plate 9.
Bills printed in Yuan era

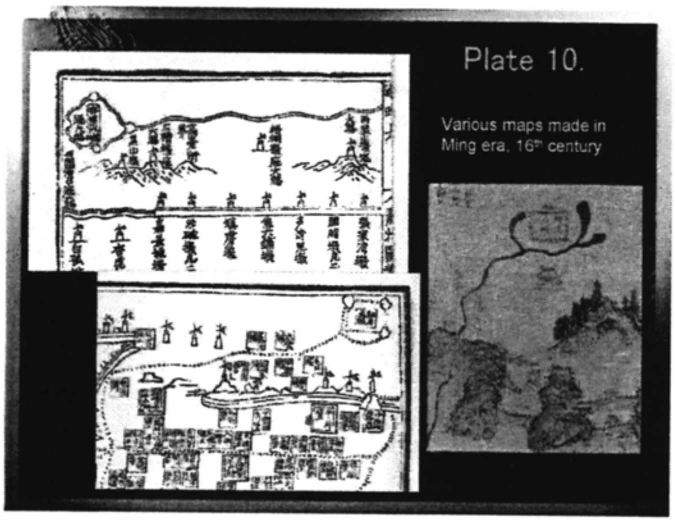
Plate 10.
Various maps made in Ming era, 16th century

# Changes in natural environment reconstructed from natural proxies in the Heihe Basin

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The natural environment changes could have caused some historical events of human activities. The past environmental conditions, such as air temperature and precipitation, have been recorded in glaciers, trees, and bottom of lakes. Physical and chemical analysis of these natural proxies can lead to the reconstruction of the past environment. In the Oasis project, we tried to reconstruct changes in natural environment in the Heihe River Basin by lake sediment, tree rings, and ice cores around the basin (Fig.1). Each proxy has different information on natural environment. Table 1 shows past information reconstructed by the proxies.

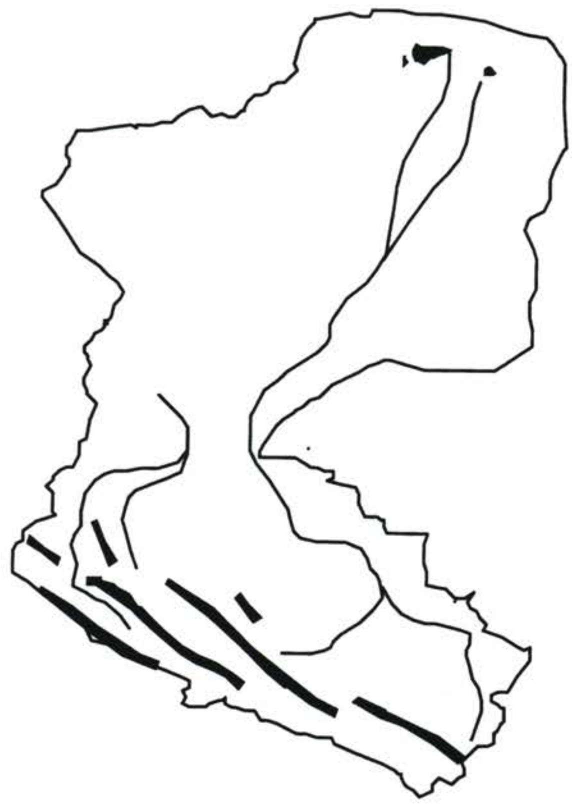

Fig.1 Natural proxies and their covering areas in the Heihe Basin

Table 1 Past environmental conditions possibly reconstructed by the proxies

| Proxy | Analysis | Information |
|---|---|---|
| Lake sediment | Microfossil | Water temperature |
| | Pollen | Vegetation |
| | Carbon stable isotope | Characteristics of lake water |
| Tree rings | Width, density | Air temp, Precipitation |
| | Carbon stable isotope | River discharge |
| Ice core | Stable isotope | Air temperature, Precipitation in the mountain area |
| | Dust | Dust event |
| | Chemistry | Forest fire, Pollution, etc |

Lake sediment cores were collected in terminus lakes of the Heife River. Analysis of pollen, microfossils, and carbon stable isotopes in the sediment revealed the changes in temperature and characteristics of lake water, and vegetations surrounding the lakes. The results also suggest changes in water level of the lakes. These changes may be strongly related with past human activities, such as agriculture and water use in this area. Detailed results are shown by Endo in this volume and elsewhere.

Tree rings were collected in the Qilian Mountains, where the Heife river comes from. We found a strong relationship between ring interval and early summer precipitation in this area. Thus, the tree rings could have climate records for last hundreds to thousands years. Furthermore, we could know changes in river discharge from the tree rings by a new method, analysis of carbon stable isotope. Samples were also collected from Tamarisk trees in desert area of the basin. They might allow us to know past climate condition in the area. Detailed results are shown by Kobayashi in this volume and elsewhere.

Two ice cores were successfully drilled in this project. One was from Dunde Ice Cap located in the Qilian Mountains and drilled in October 2002 (Fig. 2). Elevation of the drilling site was 5310 m a.s.l. This core is 51 m long and covers approximately last 160 years. In 1987, China-US joint team has successfully drilled ice cores from surface to bottom (131 m) on the same ice cap (e.g. Thompson et al. 1987). Their results showed past climate change in last 10,000 years. The main objective of our ice core is to reconstruct recent climate change after 1987. Tentative results of oxygen isotope and dust concentration in the ice core suggest warming trend for last 15 years. They also suggest increase of dust supply and decrease of mass balance of the ice cap in the period.

Another ice core was from the Belukha snow firn plateau in the Altai Mountain, Russia, which is located in northwest of the Heife river basin (Fig. 3). Elevation of the drilling site was 4100 m a.s.l. Preliminary studies have been carried out in 2001 and 2002, and then full ice core has been drilled in July 2003 (Fujita et al., 2004, Takeuchi et al., 2004). The full core is 171 m long from surface to bottom of the glacier. This core possibly covers last 1000 years. Analysis of an shallow ice core and pit samples taken in the preliminary studies showed that seasonal signals of stable isotope, chemical composition, and pollen were preserved well in the core (Aizen et al., 2006, Iizuka et al., 2004, Nakazawa et al, 2005). Although analysis of this core is still in process, this core could help our understanding sources of water vapor of the basin in wider scale of this region.

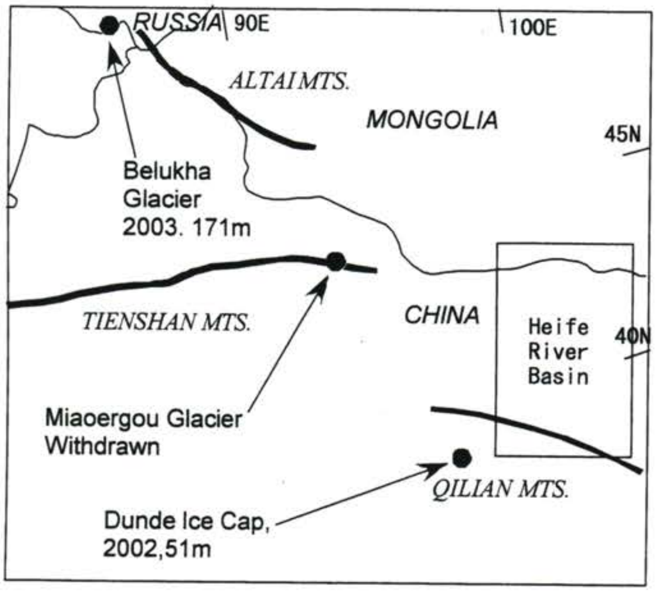


Fig. 2 Location of the glaciers where ice cores have been and have planed to be drilled in this project.

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# Paleoenvironment and Migration of rivers, delta and lakes in the lowest reaches of Heihe River

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Keywords: Heihe, paleoenvironment, inland lake, gravel bar, pollen, diatom, Holocene,Little Ice Age, sand dune, delta

Abstract

Migration of rivers and lakes in the lowest reaches of Heihe River during the last 8000 years, was investigated mainly by field observation, micro-fossil and chemical analyses of sediments, AMS datings and satellite images, in relation to the shift of delta and sand dunes. The results are summarized as follows.

From 7500 to 1700 years BP, giant Old Juyan Lake was existed just faced on the Juyan Delta. The extension of Old Juyan Lake in the past was reconstructed by the former shorelines (gravel bars) and those ages were determined by AMS method using molluscan fossils from the bar deposits. The main part of the Juyan Delta is covered with sand dunes, but traces of braided channels still preserved. Around the Green City and western half of Juyan Delta, human occupation including irrigation channels and agricultural land was dominated at least in Han Dynasty.

After AD 250, the Old Juyan Lake was dried up or became very small lakes, because no former shorelines were found. At this moment a river began to enter into Sogo Nur. Sand dune formation was activated and disturbed the river course.

Around AD 1200, Heihe channels migrated to northward, commenced to form Ejina Delta. Frequent flooding deposits are distributed and the river water reached to Gashun Nur. In Xixia and Yuan Dynasties, they used still irrigation channels for agriculture around Black City and in the western part of Juyan Delta.

During the Little Ice Age, pollen and diatom analyses indicate that Gashun Nur environment alternated between water coverage and desiccation. AD 1450 – 1550, irrigation channels were covered with Tamarix cones, suggesting abandonment of the human occupation under such arid environments in the lower reaches of Heihe.

## 1. Introduction

In order to understand "historical evolution of the adaptability in an oasis region to water resource changes", our group on topography and sediments in Oasis Project of RIHN has investigated the paleoenvironment during the last 8000 years mainly in the lowest reaches of Heihe River, in special relation to migration of rivers and lakes. Especially, we

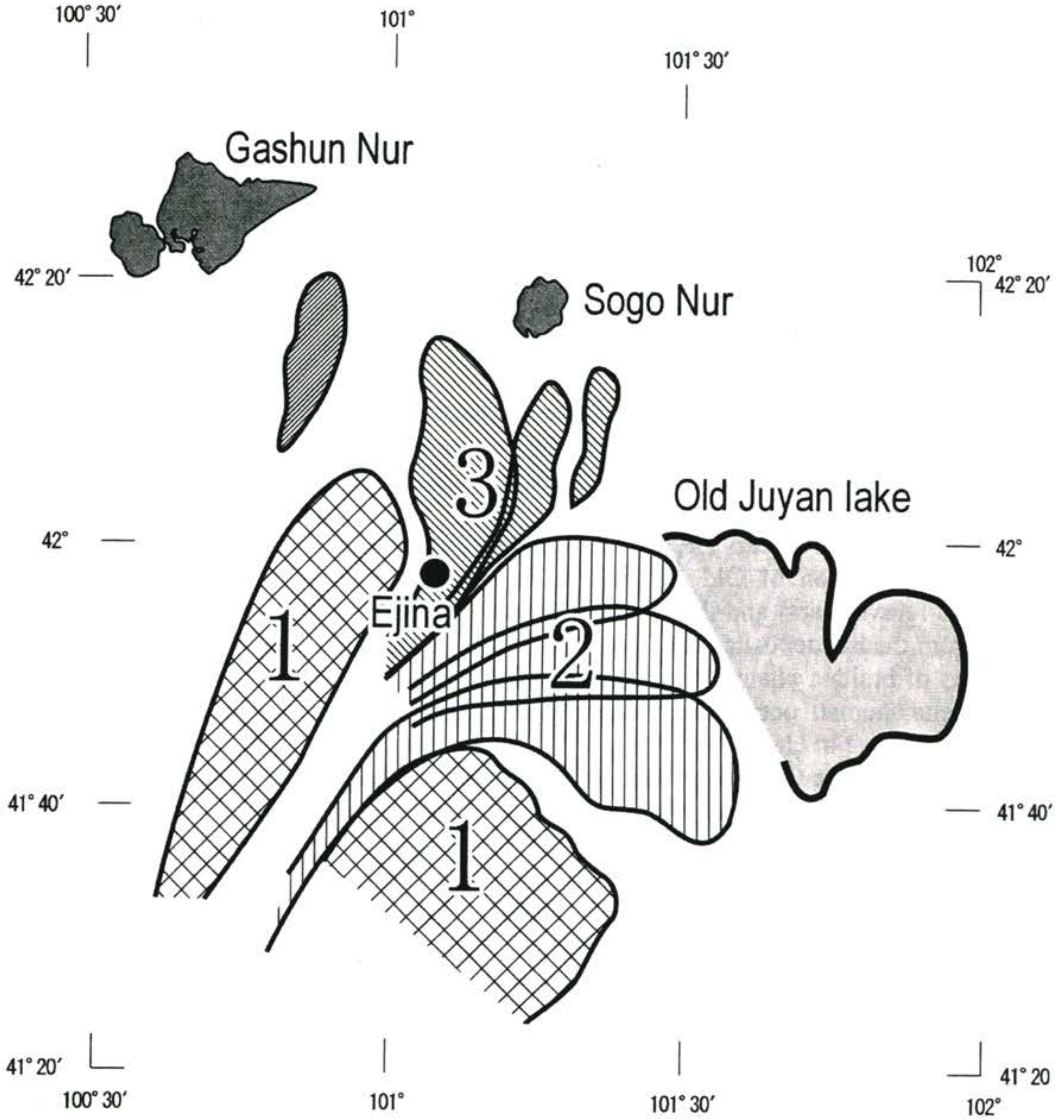


Fig.1 System of alluvial fan, delta and terminal lake in the lowest reaches of Heihe
1 : alluvial fan, 2 : Juyan Delta, 3 : Ejina Delta

examined field evidences based on topographical and sedimentological observation, in addition to micro-fossil and chemical analyses of sediments, AMS dating and satellite images. On the micro-fossil analyses, diatom and pollen assemblages were checked. Age determination is based on AMS $^{14}C$ dating, OSL dating, and historical evidences.

**2. Delta systems in the lower reaches of Heihe**

Landsat images of the lower reaches of Heihe, Inner Mongolian, show clear topographic image of alluvial fan, delta, and terminal lake. Alluvial fan, delta, and lake make a series of topographic system, and these are connected with channel system. As a result of migration of channel system, another topographic system or new combination of fan / delta / lake appears.

Fig.1 shows delta system and its evolution, namely terminal lake / delta / alluvial fan combination and channel system in the lower reaches of Heihe. Here, older alluvial fan (1), Juyan Delta (2), and Ejina Delta (3) are illustrated. The older alluvial fan is probably the late to latest Pleistocene origin, but some part may be overlapped with younger alluvial fan deposits. As for the stages of Juyan and Ejina Deltas, alluvial fan deposits distribute only in the narrow zone between dissected topographies of the old alluvial fans.

Since 7500 years BP, two delta systems with braided channels were developed and migrated in the lower reaches of Heihe as follows.

Juyan Delta System

Juyan Delta facing to Old Juyan lake, formed from 7500 to 1700 years BP, based on ages for gravel bars of the Old Juyan lake shorelines. Ages of the older Juyan lake suggest the delta date back to 7500 years BP, whose samples were obtained from the lake bottom sediment. Braided and/or sinuous (meandering) channels are dominated on the delta along with sand dunes. Such delta system, channel / delta / terminal lake, is subdivided into three sub-deltas based on difference in sinuous channel pattern (Gobi) on the Corona images. Gobi, recognized by black patterns on Corona images, is confirmed to be gravelly floor in the field. The deposits are composed of gravelly sand or sandy gravel. Surface of the deposits is gravels concentrated as "eolian lag gravel". Channels on the Juyan Delta are trending towards ENE to ESE.

Wide, whitish parts along black pattern of Gobi on the Corona images, were confirmed partly to be cultivated fields since the Han Dynasty. Their distribution pattern suggests that flood plains of both sides of the channels were exploited as cultivation fields. Black City, Green City and the surrounding areas are included in the Juyan Delta.

Since about 2500 years BP, Sogonur had gotten water area(after Germany Team), but from the gravel bar data, the lake level of the Old Juyan lake was still maintained at higher level and dropped abruptly about 1700 years BP. Therefore, from 2500 to 1700 years BP, channels toward Old Juyan lake and toward Sogonur coexisted. The channels toward Old Juyan lake blocked with sand dunes about 1700 years BP.

## 3. Environmental changes and the evidence

Table 1 Environmental History of Lower Reaches of Heihe (1) - 7500 to 1700 BP-

| Age | Events on Environmental Change | Evidence, Source, Notes |
|---|---|---|
| 7500-4000 y. BP | Formation of Old Juyan Lake and Juyan Delta | Lake gravel bars, Lake sediments [Tian-e Hu], Braided channels in sand dune area |
| 4000-3000 y. BP | Lowering of lake level, arid climate and/or sand dunes blocking river course | No gravel bars. Advancement of sand dunes |
| 3000- | After the interruption, channel system moved to north (Tian-e hu channel) | Migration of braided channels |
| 3000- | Development of Juyan Delta and braided channel system | Corona images |
| 3000-1700 y. BP | Old Juyan Lake and braided channel system in the large sand dune zone (Juyan Delta) | Ages of gravel bars and channel deposits, Corona photo. |
| 3000-2500 y. BP | Starting of blocking Tian-e hu channel with sand dunes | Sand dunes |
| | Repeating lowering and rising of water level. | Lake level changes, shown by gravel bars |
| 2500y. BP | Water commenced to enter into Sogonur | Germany Group:beginning of lake sediment |
| | After 2500 y. BP, braided channels to Juyan Lake through sand dune zone still existed. | Higher gravel bars show existence of large Juyan Lake, which needs supply of water by channels |
| 2000y. BP | Early Han Dynasty, agriculture lands and irrigation channels in large scale. After latest stage of Han, desertification dominant. | Ruins of te K710 and K688 West Han (BC206-AD8), East Han (AD25-220) Li (2004: Oasis Report, 4-2) |
| 1700y. BP (AD250) | Channel network in Juyan Delta blocked with sand dunes | No bars suggesting rapid drop of water level of the Old Juyan Lake. |
| 1700y. BP | Sogonur shallow water, littoral condition | Mischke, 2001 |
| (AD25 年) | Water flowed down to Sogonur through Ejina East Channel, making Ejina East Delta. | Topography |

7500yBP to 1700 yBP

Table 1 shows the environmental events and their evidences, source and/or notes during the period from 7500 to 1700 years BP. Main data sources are gravel bars of Old Juyan Lake, located in the surrounding area of Tian-e Hu, and lake bottom sediments around Tian-e Hu. Other data obtained from older channel deposits and sand dunes covering them are also used. Archeological sites of Han Dynasty are good tools to determine the age of delta topography.

What is main processes to change the river course ? Actually, Juyan delta areas are covered with moving sand dune zones in various places. Distribution of these sand dune

Table 2 Environmental History of Lower Reaches of Heihe (2) -1700BP to AD 1200-

| Age | Events on environmental change | Evidence, Source, Notes |
|---|---|---|
| 1700y. BP– (AD250～) | Blocking of channels with sand dune (Sand dunes covered channel networks of Juyan Delta) | Lake level drop in Old Juyan Lake (no bar → rapid drop of the level), Fixed sand dune. |
| 1400¯700y. BP | Sogonur high water level | Mischke, 2001 |
| (AD250) | Water went to Sogonur through Ejina east channel, making Ejina east delta. | Topography |
| AD250– AD1200 | Minor channels in Juyan Delta Sand Dune co-existed with Ejina East main channel. But minor channels not reach to Juyan Lake. | Water in Sogonur (Germany team) No archeological site |
| About AD1000 | Sogonur distinct drop of lake level | Ostracoda (Mischke, 2001) |
| AD1038 | Xixia founded. AD1038-1227 | Sato (Oasis Rep., 5-1) |
| | Xixia controlled this area since early 11C, built Black City. | Inoue (Oasis Rep., 5-1) |
| | Cultivated fields and irrigation channels | Corona images |
| AD1160～ | Wheat cultivation (Green City) Irrigation channel necessary. | Age of carbonized wheat |
| AD1185～ | Occupation surface near irrigation channel (Dadon west) | Ages of charcoal |
| AD1200～ | Sand dune activated. Main channel carried water to Gashun Nur, to be lake. | Diatom (lake), age of lake sediment |

zones is controlled by wind actions. Thus, wind directions determined the distribution pattern. On the other hand, vegetation cones, mainly Tamarix cones, are distributed along the both sides of Gobi, which shows the older channels.

Beginning of Sogo Nur

Mainly based on the ostracoda analysis for Sogo Nur cores, Germany group proposed a lake level change curve of Sogo Nur. They obtained a radiocarbon age from the lower part of a core, 1615±95 years BP(1700±85 conv. BP) and extrapolated the age of the beginning of Sogo Nur as about 2500 to 2100 years BP (Mischke,2001).

This means the Heihe water flow already commenced reaching to Sogo Nur about 2500 to 2100 years BP. However, in this stage, the water level of Old Juyan Lake was maintained at higher level until 1700 years BP. It suggests that Heihe water was drained toward east to Old Juyan Lake and also toward north to Sogo Nur.

During this period, Heihe water reaching to Sogo Nur must use a channel of the eastern side, near Badaoqiao, making a small scale delta (Ejina East Delta) along the channel about 2500 to 1700 years BP.

1700 y.BP to AD1200

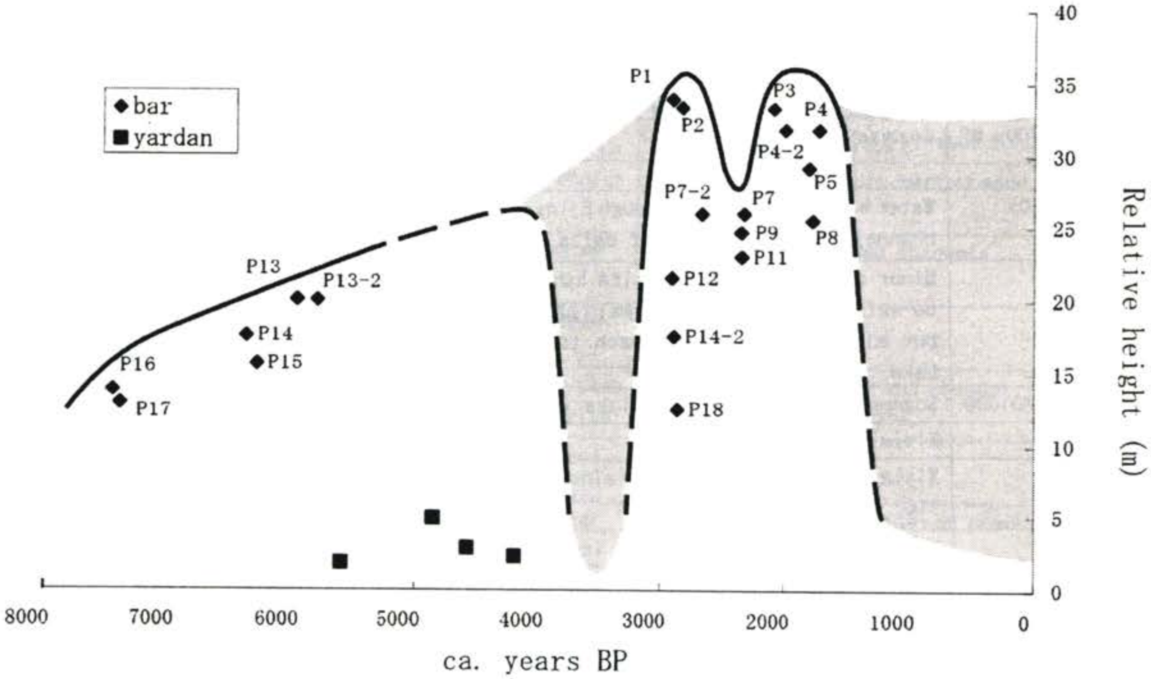


Fig.2 Lake level change deduced from gravel bars surrounding Tian-e Hu

Table 2 shows the environmental events and their evidence, source and/or other notes during the period from 1700 years BP to AD 1200.

From 1700 years BP to AD 1200, the Delta was probably in drier condition. Paleoenvironmental data are few in this term.

Older shoreline topographies, gravel bars, are distributed around Tian-e-hu and extend to much eastern part. Those are the best evidence of Old Juyan Lake. Around Tian-e-hu, nineteen gravel bars are found. 24 dating samples were taken from the test pits of each bar and from outcrops of yardan topographies which composed of lake sediments. Fig.2 shows the trend of lake level change of Old Juyan Lake, based on the dating data for older shoreline topographies around Tien-e-hu. In this curve, the final gravel bar was dated as about 1800 cal.years BP. After this bar, no evidence of gravel bars are found. Lake sediments from yardan are also older. This suggests that after 1700 years BP (AD250), lake level dropped rapidly or desiccated. Since then a lake area must have been limited in the area of lake sediment (yardan), even if existed.

Mischke(2001) analyzed ostracoda from Sogo Nur cores, and reconstructed the lake level curve during 2500 to 500 years BP. It shows higher water level from 1400 to 700 years BP interrupted with a distinct lowering centered around AD1000.

Ejina Delta formation     AD 1200 to AD 1500

Table 3 shows the environmental events and their evidence, source and/or other notes during the period from AD 1200 to AD 1500.

Table 3   Environmental History of Lower Reaches of Heihe (3)   -AD1200 to AD1500-

| Age | Events on environmental change | Evidence, source, Notes |
|---|---|---|
| AD1200～ | Sand dune developed more. Main channel carried water to Gashun Nur | Diatom living lake water<br>Age of lake sediment |
| | Irrigation channels are continuously | Artificial channel and archeological site |
| | Ejina main delta began to form<br>(by Ejina main channel et al.) | Topography |
| AD1227 | Xixia controlled by Yuan Dynasty | |
| AD1286 | Mongolian forces Black City? | |
| AD1370? | Drought, bad crops. Dry stage started ? | Oasis Meeting |
| AD1372 | Ming Dynasty destroyed Black City. | Ming Dynasty 1358-1644 |
| AD1413 | Irrigation channels still used.<br>(repaired?) | Age of channel wall. |
| AD1400～<br>(AD1350～?) | Frequent floodings,<br>Ejina delta developed actively. | Age of flood deposits on Ejina delta in the lower reaches. |
| AD1475 | Abandoned cultivation around Black and Green cities. | Ages of Tamarix cone and plant covering irrigation channel. |
| Little Ice Age or AD1400(AD1350)～ | Since AD1400 (or AD1350), Gashun Nur dried up repeatedly. | Diatom(resting spore) and pollen of Gashun Nur lake sediment. |

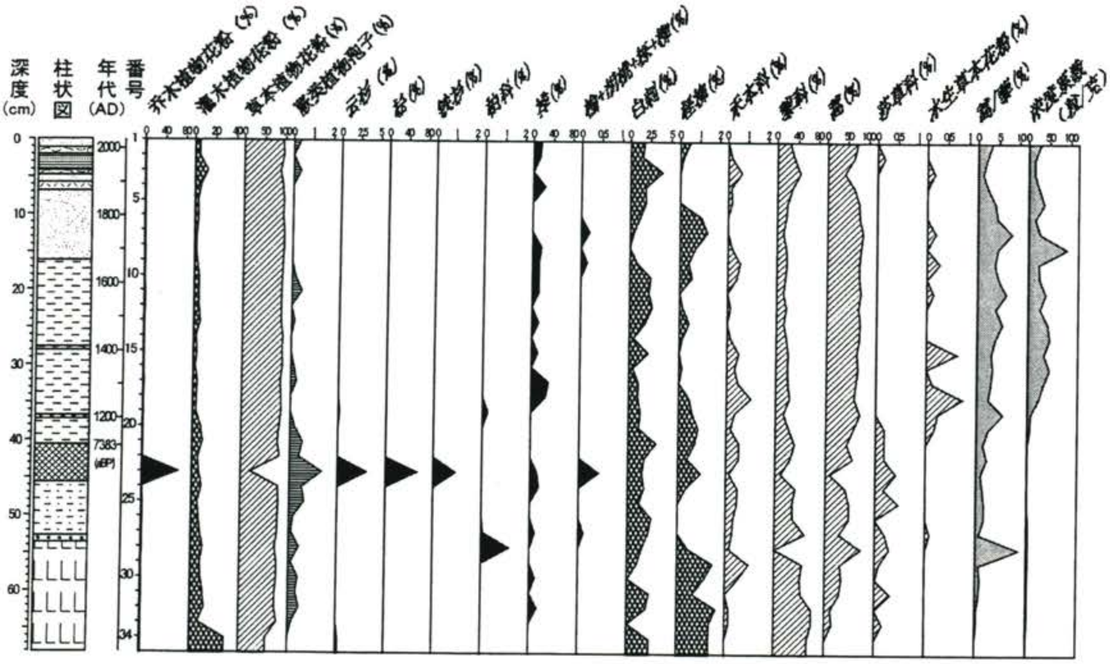


Fig.3   Pollen diagram for the deposits of Gashun Nur pit ( analyzed by Qi )

Ejina Main Delta

Ejina main channel shifted the course to north, and flowed into Gashun Nur about 1200 AD. Along this river course, Ejina main delta developed with many flood deposits. Present Ejina town and cultivated fields are situated on the delta.

In Gashun Nur, a pit of 1.5 meters deep was dug. In the profile of the pit, top 40 cm is greenish gray lake sediments, and the lower part is reddish brown thick soil. The boundary between lake sediment and reddish soil is very clear. Nearly the lowest horizon of green-gray lake sediments includes a thin layer of caliche, which is dated by AMS $^{14}C$ method to be about AD 1200. The lowest part of the lake sediment includes fresh-water diatom and aquatic pollen / spore (Figs.3 and 4). The clear boundary and big difference in environment, suggest this changing process occurred abruptly about 800 years BP.

Around that time, in Xixia Dynasty, peoples were using irrigation channels for agriculture.

Flooding increased at least 1300's AD, and was active around AD1400.

At Yingluoxia, there is a stone monument on water hazard (Kato, Inoue, 2005).

According to Dunde Ice core data by Sakai, change in temperature became

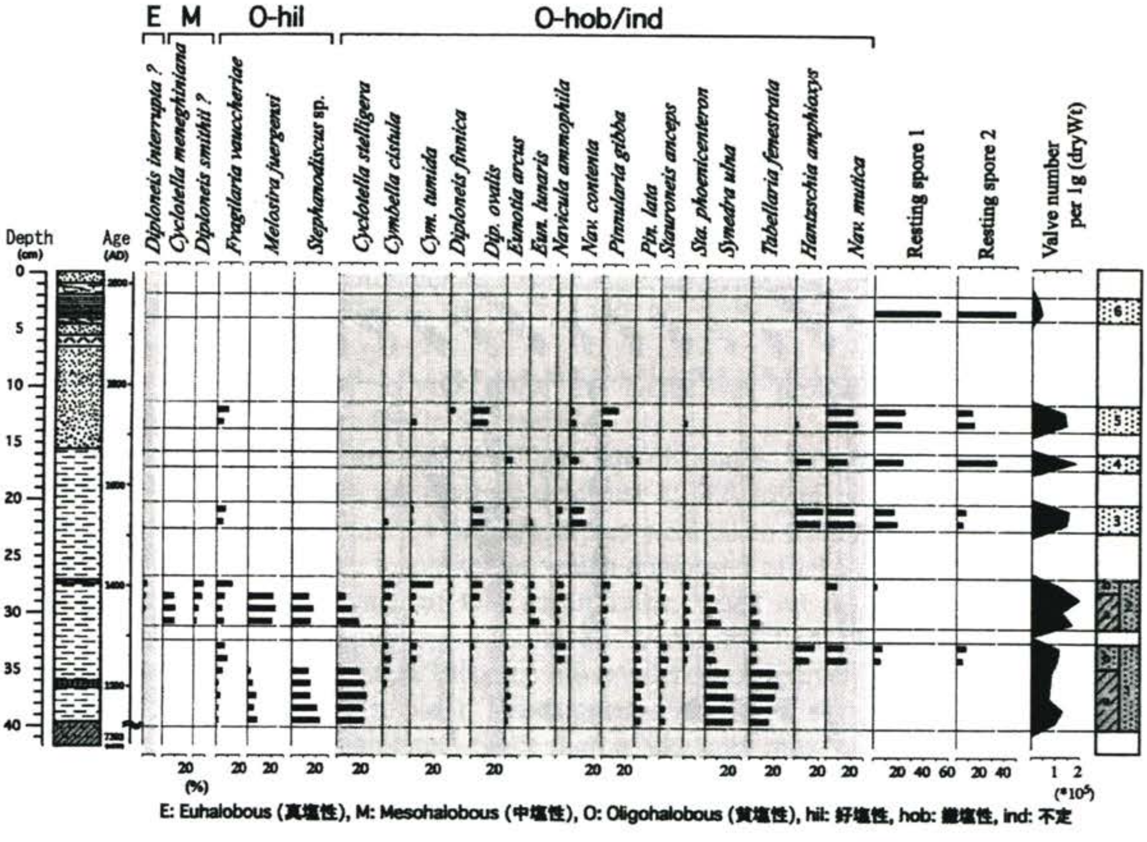


Fig.4 Diatom diagram for the deposit of Gashun Nur pit ( analyzed by Murata )

Table 4 Environmental History of Lower Reaches of Heihe (4) -AD1500 to present-

| Age | Events on environmental change | Evidence, Source, Notes |
|---|---|---|
| Age not clear | Badaoqiao channel was blocked with sand dune to be a small lake | Topography, lamination of lake sediment |
| Early half of $20^{th}$ century | Gashun Nur was a perennial lake | Hedin, Stein(after Mischke, 2001) |
| 1929 | Sogonur maximum depth 4.12m | Hedin, 1943(after Mischke, 2001) |
| Early 1930' | Big flooding from middle to lower | Grandfather of driver (査), |
| 1958 | Flooding (Ejina)<br>Sogonur surface area 35.5km² | Driver (査)<br>Gu, 1999(after Mischke, 2001) |
| 1960, 1982, 1985 | Sogonur salinity 0.6-3.4 ~5-10 ‰ | Liu, 1992 |
| 1961 Autumn | Gashun Nur dried up | Wan *et al.*, 2002 |
| 1973, 1980, 1986, 1994 | Sogonur dried up | Do |
| 1975 | East of Badaoqiao, a terminal lake dried up in 1975 | Driver |
| 1989 | Water was in Badaoqiao lake to 1989 | Driver |
| 2003 late Sept. | Water supplied in Badaoqiao lake from late September 2003, to early July 2004. 40-50cm deep. No water before long time. | Driver |
| 2004 April | Badaoqiao lake had water of 50-60cm deep, but dried up in June, 2004. | Nomad near Badaoqiao |
| 2005 Sept. | Badaoqiao lake dried up, no water | |

As a reason of the shift of channel course, advancement of sand dune should be considered, adding to other reason such as increase of river discharge and/or precipitation.

After AD 1500

Table 4 shows the environmental events and their evidence, source and/or other notes during the period after AD 1500.

Gashun Nur had dried up in 1961 autumn (Wan et al. ed.,2002). Sogo Nur had dried up in 1973, 1980, 1986, and finally 1994 (Wan et al. ed.,2002).

## 4. Discussion

Fig.5 is a model showing migration of channel/delta/terminal lake systems in the lowest reaches of Heihe during the last 3000 years .

From 3000 to 2000 years ago, Heihe flowed down to eastward in the lowest reaches, making braided channels, forming Juyan delta, and reaching to Old Juyan Lake (left one of Fig.5). During the Han Dynasty, cultivated land were distributed beside channels in the Juyan Delta area.

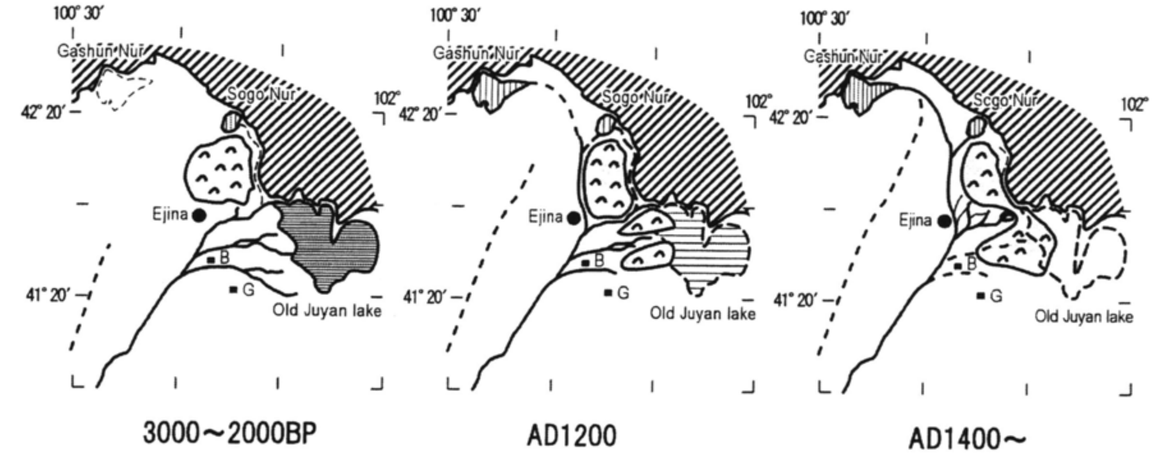


Fig.5 A model showing migration of channel/delta/terminal lake system in the lowest reaches of Heihe during the last 3000 years.
B : Black City, G : Green City

From 2500 to 2100 years BP, Heihe water commenced to reach to Sogo Nur using Ejina east channel, but the water was also supplied to Juyan delta and Old Juyan Lake. Water level of the Old Juyan Lake was very high from 3000 to 1800 almost continuously. Sand dune activity in the Juyan delta area probably started.

Around 1700 years BP, Old Juyan lake level dropped down abruptly. No gravel bar existed. Therefore, area of Old Juyan Lake was highly reduced or desiccated. As Heihe water might be mainly supplied to Sogo Nur, the water supplied to Juyan delta could not reached to Old Juyan Lake. Sand dune movement was very active and blocked channel courses.

Around AD1200, Heihe water reached to Gashun Nur using Ejina main channel to make a fresh water lake. In Gashun Nur, lake sediments overlying the reddish brown soil implies that dryer land spread before around AD 1200. Cultivation in Juyan delta area continued in the Xixia and Yuan Dynasties. They must have used many irrigation channels for agriculture in Juyan delta area.

In the eastern China, the warmest period in the last 1000 years was in the thirteenth century (Zhang, 1994). Moreover, abrupt climatic change signals on dry-wet are detected in 1217, 1266 and 1272 in most regions in the eastern China (Zhang, 1999). From the dry/wet grade curves of Zhang (1999), rapid change from drier condition to wetter condition can be detected in the thirteen century commonly in the eastern China. There is a possibility that wetter and warmer climatic condition contributed to the shift of channel course. For example, increasing of river water supply brought a large amount of clastics (sand and mud) in the lowest reaches, and drier condition under the warmer climate dominated in the desert and subdesert area strengthened transport of clastics, movement of sand dunes, generating dust and sand storms, and sometimes blocking channel courses.

After 1400 years BP, Ejina main delta has developed along Ejina main channels and its tributaries. Channel water reached to Sogo Nur and Gashun Nur to maintain freshwater lake almost continuously. During this period, channels in the area of Juyan delta were dried up, and cultivated land and irrigation channels were declined or abandoned. From diatom and pollen analyses for Gashun Nur lake sediments, drier climate condition was probably dominated in the whole lower reaches. Sometimes, flooding water reached to Gashun Nur, but water level was maintained not long time. Increase of Tamarix pollen is also temporally.

To clarify the detailed process of migration of rivers, deltas and lakes, and relationship between such change in natural condition and human activities, it is necessary to understand the following problems.

Badaoqiao (Murneng Nur) dry lake deposit is laminated very well, having 637 layers. These laminated sediments probably indicate the condition in the Little Ice Age continuously in this area. Dating of those sediments is required.

Just before the abandonment, irrigation channels in the area of western Juyan Delta had been used (West of Dadon Site). Wide cultivated lands in the Xixia and/or Yuan Dynasties are situated near the main channel or upper part of the delta (move to easier part to obtain water). Much more data concerning to cultivation lands and irrigation channels are necessary.

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## Impacts of Human Activities on the Hydrological Cycle in the Heihe River Basin, Western China

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### 1. Introduction

Heihe River is one of the biggest inland rivers in the semi-arid region of northwestern China. The Heihe River basin consists of three parts, namely the upper mountainous area which is the source of the Heihe River by rather big amount of precipitation and glaciers, the middle oasis area like Zhangye and Jiuquan, and the lower terminal arid area like Ejina. Each area has independent hydrological sytem and ecosystem. Surface runoff from the upper mountain area by rain and melt water of snow and glaciers is the only source of water available in the middle oases area and the lower arid area. Figure 1 shows the location and the outline of the study area. During past fifty years, many river courses have dried up, and the terminal lakes have vanished. This paper focuses the human induced impacts on the hydrological cycle of the Heihe river.

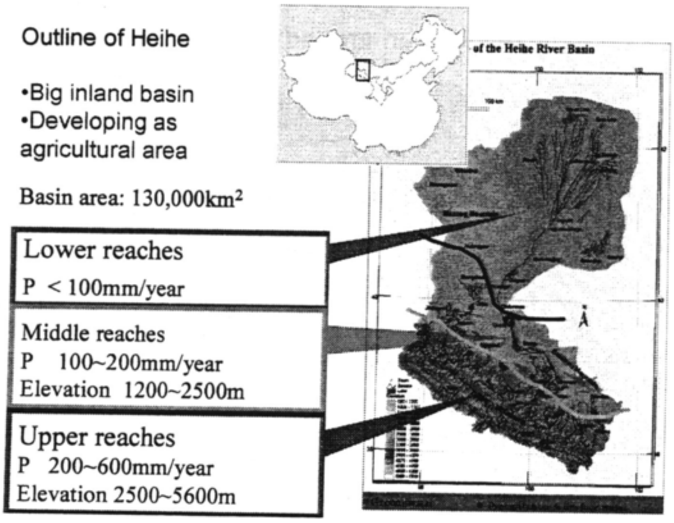


Figure-1 The outline of the Heihe river

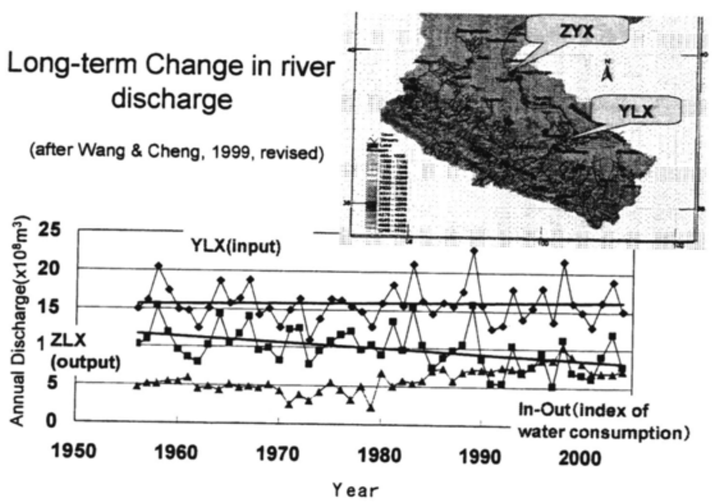


Figure-2 Long-term change in river

### 2. Water use and its effects on

**the hydrological cycle in the middle reaches**

Figure 2 shows changes in amounts of incoming water to the middle reaches and outgoing water to the lower reaches during past 50 years. The differences between two is an index of water consumption of the middle reaches. Although the river discharge from the upper mountain area has a slightly increasing trend during past fifty years, the increase of water consumption in the middle oases area mainly by irrigation for agricultural land has caused the serious shortage of water resources and the degradation of vegetations in the lower arid area. Recently, the extracted volume of groundwater significantly has increased due to the high cost of river water irrigation and the intensive water use for newly introduced cash crops (Fig.3). At 2000s, groundwater contributed 25% to the total irrigation water (Fig.4). The intensive extraction of groundwater near the city area for cash crops has caused the rapid decline of ground water table (Fig.5 and 6). Possible damage on groundwater resources should be considered.

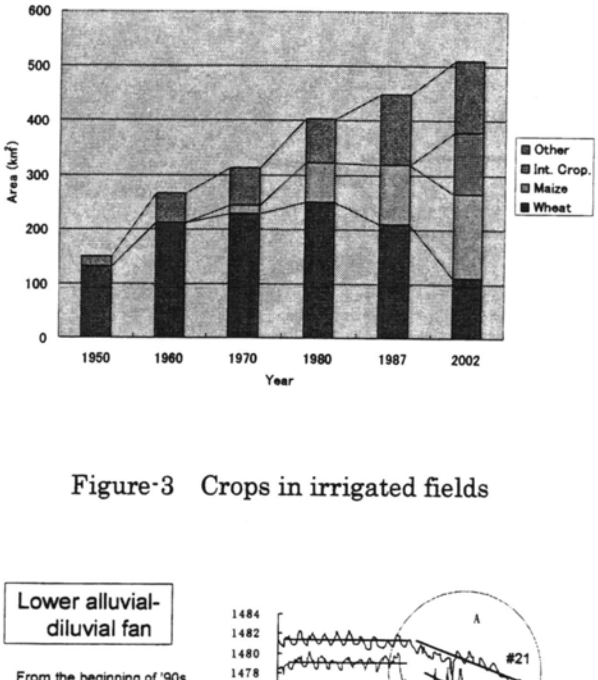


Figure-3 Crops in irrigated fields

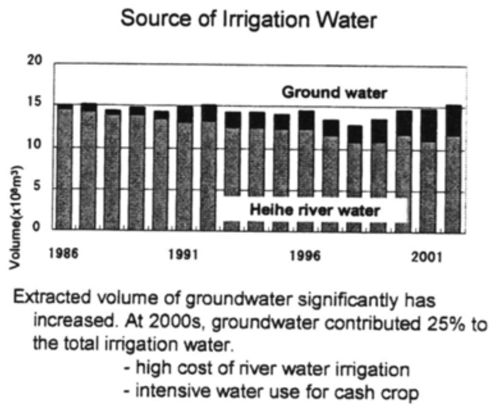


Figure-4 Source of irrigation water

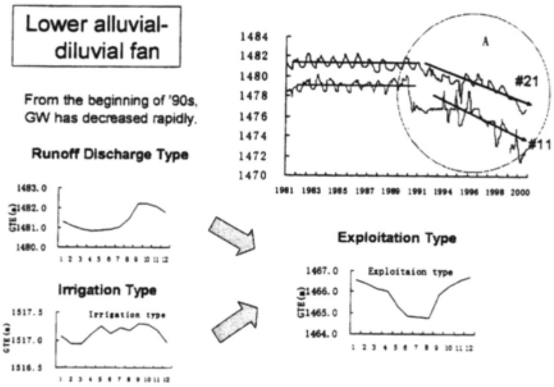


Figure-5 Change in groundwater level

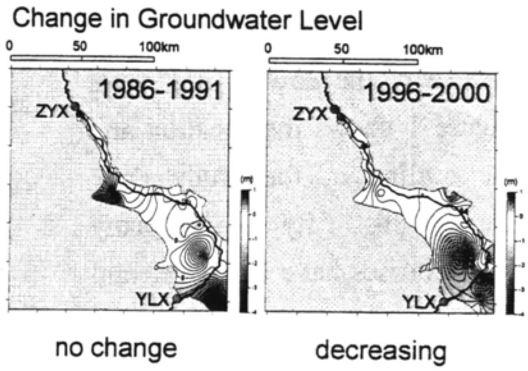


Figure-6 Distribution of Groundwater Change

Fig.7 shows comparison of annual water budget of the middle reach in 1970 and 2004. While, in 1986, over 80% of river water had been irrigated to agriculture fields and 70% of discharge to the lower reaches came from groundwater, both irrigated water and outcome from groundwater have decreased.

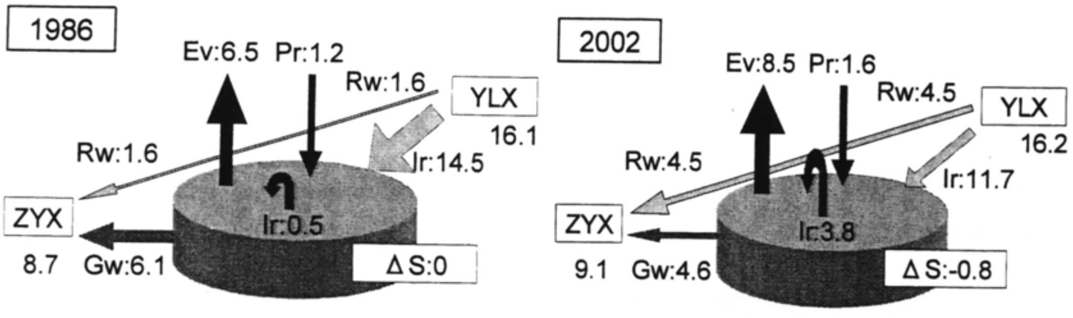


Figure-7 Annual water budget in 1986 and 2002

**3. The hydrological cycle in the lower reaches**

The lower reaches have been suffered from serious water shortage because of heavy and increasing water consumption in the middle reaches. River water sometimes has dried up. Especially, there has been almost no river water in summer except flooding. It is hard to use river water constantly and people heavily depend on groundwater resources. But the shortage of river water also has resulted in the decline of groundwater level, especially in the terminal area. So, it is important to clarify the recharging processes of groundwater, such as source and recharging amount (Fig-8-Fig-11).

(1) Source of groundwater at the desert area

Figure 12 shows the isotopic diagram of various kind of water in the lower reaches. The isotope analysis indicated that groundwater in the desert area have been recharged by rain water. In other areas, the source of groundwater is river water.

(2) Source of groundwater around the river courses

Figure 13 shows the mixing ratios of groundwater in the lower reaches. In the south area in the lower reaches, the mixing rations were around 0.5, indicating both the summer flood water and the winter water contributed groundwater recharge. The number of days on which river water exists shows better correlation with groundwater increase rather than that of river discharge. On the contrary, the mixing ratios in the north area became higher along the river. This suggests winter recharge is more important in the north area because river water rarely reached the north and terminal area in the lower reaches.

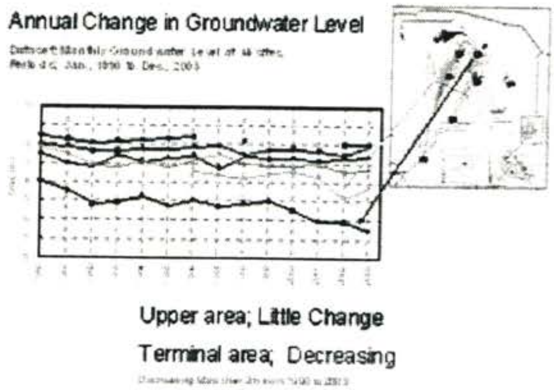


Figure-8 Annual change in Groundwater level

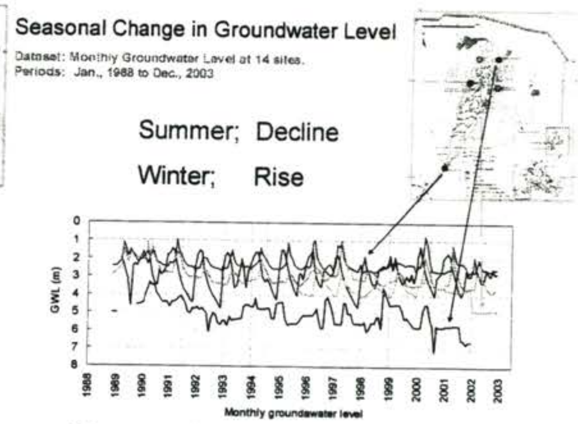


Figure-9 Seasonal change in Groundwater level

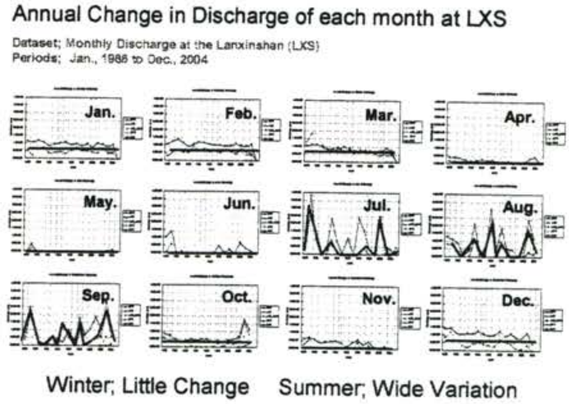


Figure-10 Monthly incoming discharge to the lower reaches

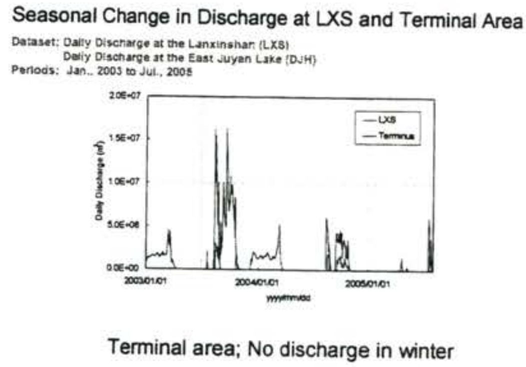


Figure-11 Seasonal change in river discharge at the terminal area

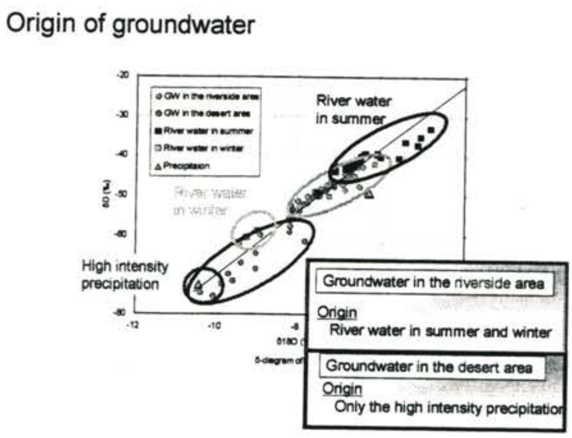


Figure-12 Origin of groundwater

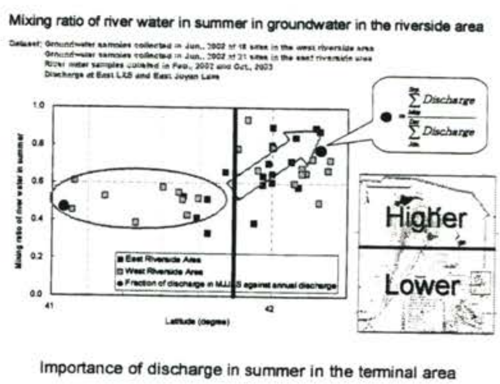


Figure-13 Mixing ratio of groundwater

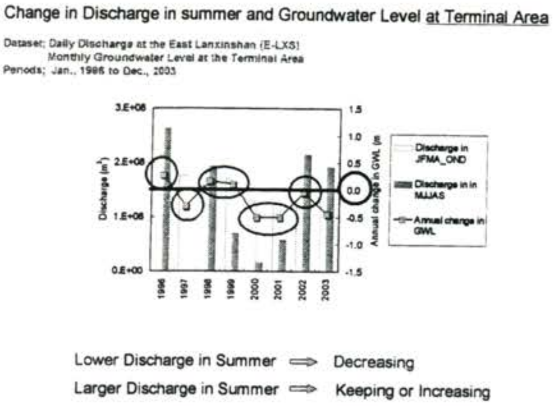


Figure-14 Relationship between summer river discharge and groundwater level in the terminal area

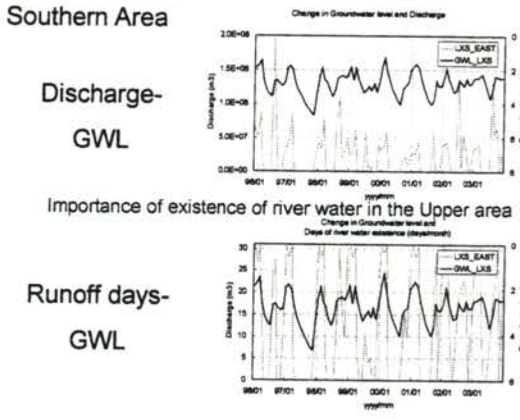


Figure-15 Relationship between river discharge and groundwater level in the upper area of the lower reaches

# The impacts of human activities on the groundwater system in the middle reaches, Heihe River basin

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## Part 1: Changes of hydro-geological system under the influence of human activites in the middle reaches (Zhangye city), Heihe River basin

### Introduction

The Heihe River basin, the second largest inland river basin in the arid region of northwest China, is located between 96 42' E - 102 00' E. The middle reaches of the Heihe River watershed, where the study was undertaken, were located in the central portion of the Hexi Corridor, Gansu province, including the counties of Minle, Linze and Goatai, and Zhangye city,. The middle reaches of the Heihe River watershed, totalling 4.08□ $10^4 km^2$ in area (Fig.1), receive between 250 mm $yr^{-1}$ in the mountainous areas of the south, to less than 100 mm $yr^{-1}$ in the northern high plains area. Under the influences of landforms, climate and vegetation, zonal soils are formed from the south (Qilian Mountain) to the north plain area: black soil, mountain chestnut soil, sierozem, grey desert soil, grey brown desert soil and blown sand soil, in addition to zonal soil types including meadow soil and aquisoils occurring in the Zhangye and Linze regions. Land types in the study area can be divided into: mountain meadow grassland, piedmont desert steppe grassland, agricultural land (includes cropland, forested land and garden land), plain swamp meadow grassland (including tree and shrub grasslands), and gobi and desert sandy land.

In hypsography, it is slanted from southeast to northwest with the elevation ranged between 1414-3616m asl. In large scale, the physiognomy of the study area can be divided into south corridor plain and north Longshou Mountain. The south plain area is slanted from southeast to northwest with a slight gradient of 25-4‰, and have a complanate land surface. From south mountain side to plain center, the corridor plain was divided to two sub-grade physiognomy types, i.e. alluvial and diluvial gravel plain and alluvial granule soil plain. At present, the granule soil plain was the main agriculture area of Zhangye city.

Due to the large-scale land reclamation and water resources development, many rivers have been reduced to oases, the water distribution status of the river system has changed greatly since the 1970s in the study area, and the ground water system was disturbed heavily. In recent 20 years, groundwater table changed greatly and the spring water declined by more than 50%. For recognizing the hydrological cycle and it change under human activities, rational utilization of water resources and efficaciously protecting the eco-environment of the study area, it is urgently demanded to research the dynamic changes of groundwater system.

## 1. Conditions of ground water formation and movement

### 1.1 Groundwater types and spatial distribution

Based on the geological materials and some hydrological characteristics of aquifer, the grounder water in the Zhangye city can be divided into unconsolidated sand and gravel aquifers groundwater, semiconsolidated sand and sandstone aquifers groundwater, carbonate-rock aquifers groundwater and Pre-Miocene old indurated rocks aquifers. Each of the four categories occupies a different hydrogeologic setting, and is characterized by water storage, aquifer recharge conditions and distributing area.

1.1.1 Unconsolidated Sand And Gravel Aquifers Groundwater

Unconsolidated sand and gravel aquifers groundwater was the main type of groundwater in the corridor plain where Zhangye city located. At present, it was also the only utilization aquifer in the study area. According to the aquifers matter composition and forming way, the unconsolidated sand and gravel aquifers can be grouped into the following three categories: basin-fill aquifers, referred to as valley-fill aquifers in many reports; blanket sand and gravel aquifers; and stream-valley aquifers.

*Basin-Fill Aquifers*

These aquifers are also commonly called valley-fill aquifers because the basins that they occupy are topographic valleys. Fine-grained deposits of silt and clay, where interbedded with the porous sand and gravel, form confining units that retard the movement of ground water. The sediments that comprise the basin-fill aquifers mostly are alluvial deposits, but locally include windblown sand, and fluvial sediments deposited by streams that flow through the basins. The alluvial deposits consist of sediments eroded by streams from the rocks in the mountains adjacent to the basins. The sediments eroded, transported, and deposited by the streams are the principal material of basin-fill aquifers. The streams transported the sediments into the basins and deposited them primarily as alluvial fans at the base of the mountains. The coarser sediment (boulders, gravel, and sand) was deposited near the basin margins and finer sediment (silt and clay) was deposited in the central parts of the basins (Fig.1).

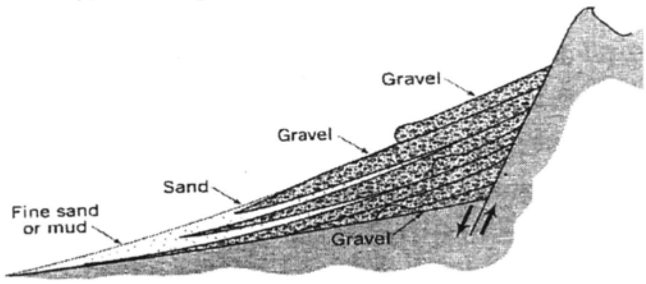



Figure 1. Diagrammatic cross section of the sediments in an alluvial fan from mountain adjacent to basin centre

In the study area, this type aquifer distribute widely in Zhangye basin and Shandan basin as the main type of unconsolidated sand and gravel aquifers, and it occupied the most area of corridor plain. Two geomorphic landforms can be distinguished on the basis of the gradient of the land surface in study area. Alluvial fans border the mountains and have the steepest surface slopes and the coarsest sediments. Basinward, alluvial fans flatten, and form alluvial slopes of moderate gradient or with a flat surface. Controlled by the geological tectonic and topographic conditions, from south mountains adjacent to the basins center, the aquifers become thick and complex, the sediments finer and water table shallow, and the aquifer become from single and under unconfined, or water-table aquifer to multi and confined complex aquifer system (Fig.2). The depth of groundwater table is generally more than 200m in upper alluvial fans near the mountain adjacent, 50-150m in middle alluvial fans south side of Zhangye city, and 10-20m in lower part of alluvial fans and fine soil plain around Zhangye city area. In northwest area of Zhangye city and near the valley of Shandan river and Heihe river, the depth of groundwater become less than 5m.

The unconsolidated sand and gravel aquifers fill consists mostly of unconsolidated deposits of Miocene and Pliocene through Holocene age. There are the largest of sediments thickness in basin center near Zhangye city with a deposit of 300-500m. Mountains adjacent ward both south and north side, the sediments thickness becomes thinner with general thickness of 50-100m (Fig.2). Generally, the groundwater storage capacity and the degree of groundwater resources abundance are scaled by single well water yields per day or minute. The unconsolidated sand and gravel aquifers have the well water yields ranged between 1000-5000$m^3$/d in most study area. The largest storage was located in the lower part of Heihe river and Liyuan river alluvial fans with the well water yields more than 5300 $m^3$/d. In north and south mountains adjacent area, however, the well water yields was less than 800$m^3$/d.

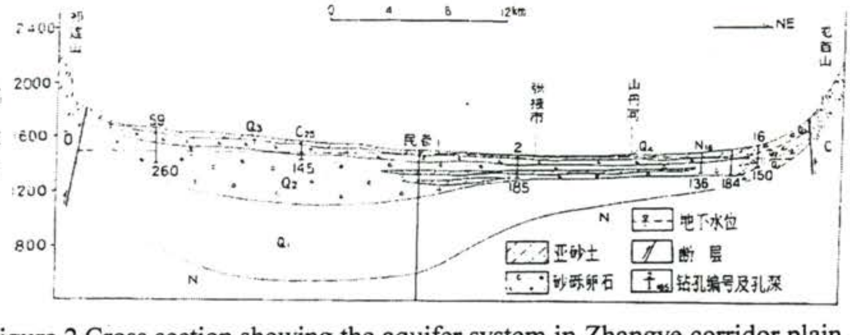



Figure 2 Cross section showing the aquifer system in Zhangye corridor plain

*Stream-Valley Aquifers*

Stream-valley aquifers, is located beneath channels, floodplains, and terraces in the valleys of major streams. The sediments deposit in Quaternary, and the thickness varied in large scale at different stream valley. There are 17 streams formed from Qilian Mountains and delivered to the corridor plain in the study area, and 4 larger rivers such as Heihe river, Suyoukou river, Dayekou river and Daciyao river. In these stream-valleys, the unconfined aquifers, consists of coarse sand and gravel, was formed in valley sediments. The aquifer have 2-20m thickness and less than 5m water table depth. The groundwater storage capacity and the degree of groundwater resources abundance are indigent in the Qilian Mountains' stream-valley aquifers with the well yields less than 100$m^3$/d.

In the Longshou Mountains area, there are about 9 streams delivered to the corridor area. The stream-valley aquifers consist mostly of coarser sediment (such as boulders, gravel and coarse sand), and the thickness is generally ranged 2-10m. Due to the folium aquifer and largely varied precipitation, the well yields were ranged between 4.32-348.2$m^3$/d with the groundwater table varied from 1m to 6m.

*Blanket Sand And Gravel Aquifers*

Widespread sheet-like aquifers that consist mostly of medium to coarse sand and gravel are collectively called blanket sand and gravel aquifers. These aquifers mostly located in both south and north side of the corridor plain, and contain water under unconfined. Locally, where stream-valley alluvial aquifers, which also consist of sand and gravel, cross the blanket sand and gravel aquifers, the two types of aquifers are hydraulically connected. As mentioned above, both south and north corridor plain side, there are about 26 streams with short river way and formed many little alluvial fans allied each other. The blanket sand and gravel aquifers largely consist of those allied little alluvial deposits, however, there are large areas of windblown sand and water erosion or both along the adjacent mountains.

The aquifer thickness varied spatially, and ranged between 20-150m. The groundwater tables unconfined have depth of mostly larger than 100m, with a sharp slope slanted to basin center. Blanket sand and gravel aquifers have a middle groundwater storage capacity, generally, the well water yields was about 1000-3000$m^3$/d per 5m water table decrease.

1.1.2 Semiconsolidated Sand And Sandstone Aquifers Groundwater

Sediments that primarily consist of semiconsolidated sand, silt, and clay, interbedded with some carbonate rocks, consist sequences of Mesozoic and Paleozoic semi-consolidated sand and sandstone layer. The aquifer was comprised of both porous media and fracture media aquifer, extent along the Qilian Mountains and north Longshou Mountains(Fig.3). The semiconsolidated sand and sandstone aquifers have been grouped into three aquifer systems that were distinguished with sediments types and water storage conditions.

*Carboniferous and Triassic Aquifer*

The aquifer consists of sediments deposited in sea and terrestrial alternation environment, such as limestone, sandstone, mudstone and shale in Carboniferous and Triassic age, and mainly distribute in some local parts of Qilian Mountains' north side. Including both porous and fracture water content media, the aquifers have a less spatial extent area and were broken up to pieces by fault fractured zone, therefore, the aquifers have a very indigent water storage capacity. In the study area, the aquifer was mostly comprised of Carboniferous and Triassic sandstone with a single spring water yields of 0.05-0.1l/s. In some mountain parts of Shandan county, well water yields can reached to 0.07-0.16l/s with water table declined 5-8m in Carboniferous aquifer.

*Jurassic and Cretaceous Aquifer*

Sediments that primarily consist of coarse sandstone or gravel sandstone and sandstone interbedded with mudstone and shale, were deposited in lake and mountain environment during Jurassic and Cretaceous age. The Cretaceous aquifers are mainly distributed in the upper reach of Liyuan river and Daciyao stream at the north slope of Qilian Mountains and in Pingyi and Yangtai village of south Longshou Mountains. The Jurassic aquifer was distributed only in some parts of north Longshou Mountais.

Jurassic and Cretaceous aquifer retains mainly the sand porous water content media, and have a lower porosity and permeability. The water storage capacity and water resources abundant degree were varied with the various sediments, and the well water yields ranged between 0.5-256.5$m^3$/d for water table declined to 5-8m. In Qilian Mountain area, the well water yields mostly ranged 22-256.5$m^3$/d, and it changed to 2-12.4$m^3$/d in north Longshou Mountain area.

*Pleistocene and Tertiary age Aquifer*

Sediments that primarily consist of semiconsolidated sand, gravel and coarse sand, silt interbedded with mudstone. The aquifer was distributed extensively in the both side of corridor plain near pro-mountains. At present, the thickness has not being confirmed, but its' porosity and permeability was better than the other two types of semiconsolidated sand and sandstone aquifers. The water storage capacity varies greatly with the varied sediments from place to place. In south side of Zhangye basin, the well water yields ranged between 10-100m3/d for no water table decline, and when the water table declined to 5m, the single well water yields could reache to more than 2000$m^3$/d.

### 1.1.3 Carbonate-Rock Aquifers And Pre-Miocene Old Indurated Rocks Aquifers Groundwater

*Pre-Miocene bedrock aquifer*

The rocks of the aquifer system, exposed in large areas of Qilain and Longshou Mountains (Fig.3), are the basal rock in the study area. The aquifer system consists of layered rocks, such as sandstone, shale, quartzite, pegmatite, et al., deposited in Cambrian, Ordovician, Carboniferous and Silurian age. Those old bedrocks, undertaken folding and faulting of geological construction movement following lithification and erosion, formed greatly construct cranny and fracture. The geological construction action type and sediments texture complicate the movement of water through these rocks and controlled the water storage capacity.

In Qilian Mountain area, the aquifers have a runoff modulus ranged from 0.1-20.0l/s per square kilometers, and the single spring water yields ranged between 0.001-3.7l/s. In Longshou Mountain area, the groundwater runoff modulus is about 0.05-1.0 l/s per square kilometers, and the single spring water yields are generally less than 1.0 l/s.

*Carbonate-Rock Aquifers*

Aquifers in carbonate rocks are most prominent in the Longshou Mountain area in the study area. Most of the carbonate-rock aquifers consist of limestone, but locally have dolomite and marble deposited in Paleozoic and Upper-middle Carboniferous age. Carbonate rocks develop connective fractures and faults, and even locally develop some dissolution pore space. Such pore and fractures enhance the permeability and water storage capacity in the aquifer. However, due to the greatly variation of the sediments texture, geological construction actions and local precipitation conditions, the aquifer permeability and water storage capacity varied from place to place, and the single well water yields ranged between 0.5-256.6m$^3$/d.

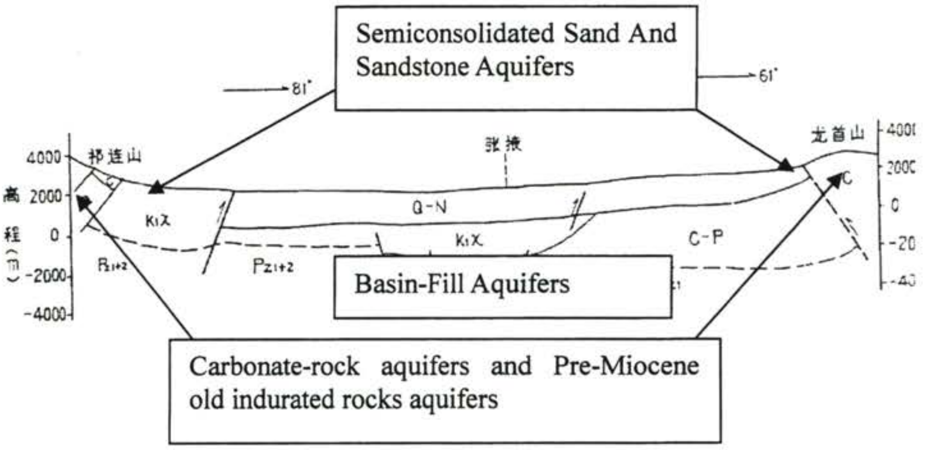



Figure 3 Cross section showing the sediments and groundwater types distribution

## 1.2 Conditions of groundwater recharge and discharge

1.2.1 Groundwater recharge and discharge in corridor plain

In arid inland river basin, Each basin has essentially the same characteristics-the impermeable rocks of the mountain ranges serve as boundaries to the groundwater flow system, and have a individual unit of groundwater system, including the mountain recharge, flow in plain and discharge in fine earth plain and terminal lake or area. In Zhangye city, most recharge to the basin-fill deposits originates in the Qilian mountains as rainfall and snowmelt, and, where the mountain streams emerge from bedrock channels, which form rivers and streams outflow from mountains, the surface river water infiltrates into the upper alluvial fans, where the sediments consist mostly of gravel and coarse sand, and have great permeability. The infiltrating river water replenishes the basin-fill aquifer. Such way is the dominating recharge of groundwater in the Zhangye basin (Fig.4). Intense thunderstorms may provide some direct recharge to the basin-fill deposits in local groundwater table buried less than 4 meters, but, in most cases, any rainfall that infiltrates the soil is either immediately evaporated or taken up as soil moisture; little water percolates downward through the unsaturated zone to reach the water table in the basins.

Another source of groundwater replenishment in the corridor plain aquifer system is interflow from mountain aquifers, which was called as basin side interflow recharge. The bedrock is sufficiently permeable to allow all recharge to flow through it and out of the mountain area, and then traverse through the pre-mountain fault and flow into deep basin-fill aquifers. The Zhangye basin is surrounded by bedrock from south and north side that is sufficiently permeable to conduct flow into the basin. The recharge volume could reach to 13% of total replenishment in the corridor plain. At present, the average volume of recharge by interflow was about $0.445\times10^8 m^3/a$ (Table 1), between that, $0.436\times10^8 m^3/a$ was from Qilian Mountain area and $0.009\times10^8 m^3/a$ was from Longshou area.

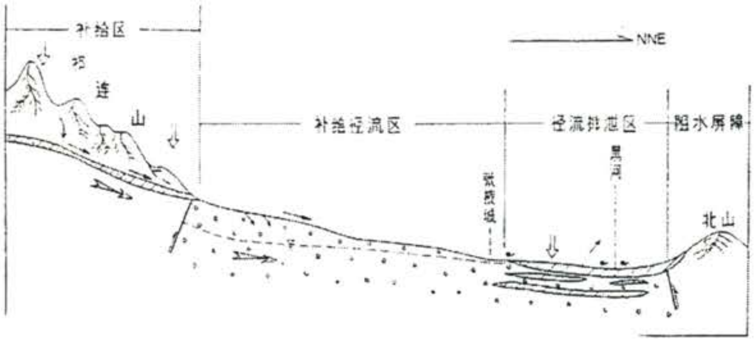



Figure. 4 Cross section showing the groundwater recharge, flow and discharge in Zhangye basin

The return water recharge from irrigation is the third source of groundwater replenishment, which was called "no-point infiltrating". At present, the infiltrating replenishment by irrigation canals and fields is calculated approximatively to $1.99\times10^8 m^3/a$ (Table 1). But the replenishment occurred in the area of groundwater table less than 10m.

Table 1 Recharge of groundwater in Zangye basin at present (1997)

| Infiltrating way | River water | Flood runoff | Irrigation canal | Irrigation field | Inter flow | Condensation and rainfall |
|---|---|---|---|---|---|---|
| Replenishment volume ($10^8 m^3/a$) | 2.916 | 0.124 | 1.836 | 0.163 | 0.445 | 0.067 |

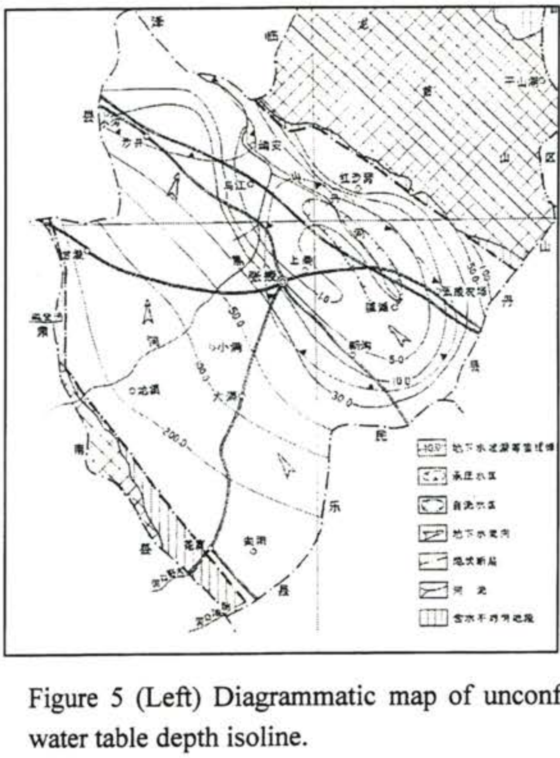
The direction of groundwater is almost same as river, warding to basin center with the hydraulic gradient of 5‰-6‰, and then flow to northwest with the hydraulic gradient of 1‰ -2‰. At the fine earth belt of alluvial fans in corridor plain or basin center, due to the lower transmissivity and declined landsurface in topographic, the groundwater table rises. Such aquifer conditions provide groundwater outflow from aquifer to landsurface by spring. In the points, groundwater discharged by evapotranspiration and spring. The volume of groundwater discharged by evapotranspiration and spring occupied about 70% of total groundwater discharge in Zhangye basin at present (1997).

1.2.2 Groundwater recharge and discharge in mountain area

In mountain area, relatively heavy precipitation forms the surface runoff, at same time, there are some rainfall replenishes the semiconsolidated sand and sandstone aquifers and bedrock fracture aquifers. The steep canyons and gulches, incised by hydraulic net, discharged the aquifer. However, some groundwater locaaly emerged from bedrock aquifer and reforms the Stream-valley aquifers and delivered to Zhangye basin ultimately.

### 1.3 Unconfined groundwater and confined groundwater

Unconfined aquifer, extensively distributes in every type aquifer and the whole study area, is the fundamental elements of Zhangye city groundwater system. Near the both south and north mountains area, called pro-mountain adjacent high plain, the unconfined aquifer has a single layer and simple sediments texture consisted primarily of coarse sand, gravel and boulders. The depth of free groundwater table ranged 100-250m in south Qilian mountain adjacent area, and 50-150m in north Longshou adjacent area. In tail of alluvial fans marched with fine earth plain, unconfined aquifers changed from single layer to multi-layer, where the confined aquifers therefore were formed, and sediments consist consist mostly of fine-grained sand, interbedded with silt. The single aquifer has an average 20-30 thicknesses. As showed in Figure 5, the unconfined aquifer distributes primarily in south of Zhangye basin, i.e. Xiaoman, Daman, Shigangdong, Xiaohe and Ganjun villages, et al.. From south mountain adjacent area to basin center, the unconfined aquifer water table rise, and the depth changed from more than 200m to 5-10m. Even around Zhangye city, such as Sangqi and Wujiang villages, the unconfined aquifer water table depth is less than 3m and overflow to surface by spring.



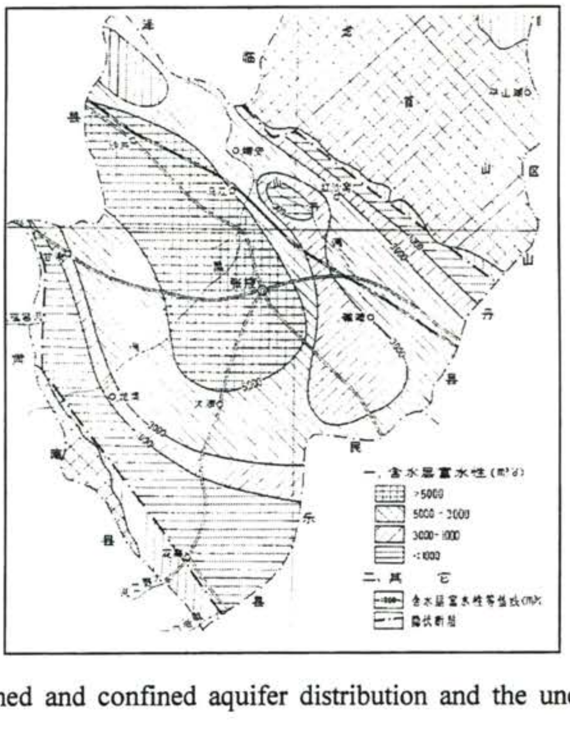


Figure 5 (Left) Diagrammatic map of unconfined and confined aquifer distribution and the unconfined water table depth isoline.

Figure 6 (Right) Diagrammatic map of the groundwater yields capacity isoline.

Generally, there are abundant groundwater resources in Zhangye basin. As showed in

Figure 6, the unconfined aquifer has a water yields capacity more than $3000m^3/d$ in most area of Zhangye basin. As same as the groundwater hydraulic gradient distributes spatially, the groundwater yields capacity of unconfined aquifer is increased from south mountain adjacent area to basin center, and there are maximum water yields around the central part with well water yields more than $5000m^3/d$, however, the water yields capacity is generally less than $500m^3/d$ near the adjacent mountain area.

There are two main area of confined aquifer distribution in Zhangye basin (Fig.5). One is just in east north area of Zhangye city town, including Shangqing, Wujiang and Pingyuanbu villages, et al., another in Linze county, including Liaoquan village, Xiaotong village and Xinhua Farm. Where the confined aquifer distributes primarily there are complex aquifer texture and relationship between more than 3 layers of aquifers. The confined water head are generally out of the surface and support first unconfined groundwater outflow to surface with together by spring. The confined aquifer consists primarily of sand and gravel with little silt. The overlying and underlying low-permeability confining beds are composite of clay and silt with a greatly varied thickness. The water abundance degree or water storage capacity was nearly same in confined aquifer distribution area with mostly the well water yields more than $5000m^3/d$.

# PART 2: The temporal-spatial variations of groundwater table in the middle reach of Heihe River Basin.

## 1. Introduction to analysis of groundwater table variation

The temporal-spatial variations of groundwater table, which reflect the forming and varying regulation of groundwater system, are controlled by precipitation, surface runoff and human activities. As an information output of groundwater system responding to outer influence factors, the groundwater table variation is an important way to understand the human influence degree on groundwater system, the changing trend and rate of groundwater system. There fore, the regulation of groundwater table variation is the essential bases to groundwater management, catchment development plan and eco-environment protection.

Since 1980, there were about 54 sites for groundwater table observation set up along the Heihe river in Zhangye basin. Those observation sites distributed in different hydrogeological unites. Controlled by geographical type, sediment characteristics and geological construction conditions, the aquifer system varied from single unconfined aquifer in south pro-mountain to multi-layer and confined aquifer system in north basin center area, and the groundwater table depth become shallower. According to topography, aquifer structure, groundwater recharge and discharge conditions and irrigation water source, the study area, middle reach of Heihe river basin, is divided into four sub-regions. For each sub-region, some basic information, such as the spatial distribution, natural characteristics, hydrogeological features, irrigation water source and observation points distribution, are listed in Table 1.

Table 1 Sub-regions and their some basic information

| Sub-region | Distribution scope and nature term | Hydro-geology and irrigation condition | Distribution of observation points |
|---|---|---|---|
| Upper-middle of the alluvial and diluvial fan | Located in south pro-mountain alluvial and diluvial Gobi plain with the elevation between 1500-2800m and precipitation of 120-300mm. | Single unconfined aquifer, groundwater table depth> 30m; mainly used river water to irrigation. | Zhangye 6#, 8#, 14# |
| Lower part of the alluvial and diluvial fan | Intersection of alluvial and diluvial Gobi plain with the fine-grained soil plain with elevation between 1400-1800m and precipitation of 100-250mm. | Conversion from single unconfined aquifer to multi layer confined aquifer with the water table depth between 8-30m; ground water mixed with river water for irrigation | Zhangye 3#, 4#, 5#, 11#, 13#, 21# |
| Fine-grained soil plain | Located in Zhangye city area of the fine-grained soil plain with elevation between 1300-1600m and precipitation of 100-150mm. | Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation | Zhangye 1#, 2#, 18#, 15#, 25#, 28#, 29# |
| River valley plain of Linze and Gaotai county | Located along the river in Linze and Gaotai county with elevation between 1270-1500m and precipitation of 60-130mm. | Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation | Linze: 11#-23#; Gaotai: 1#-16# |

## 2. The spatial variation types of groundwater table with long-term annual series

### 2.1 The trend of groundwater table variations in the upper-middle part of the alluvial-diluvial fan

In the upper-middle part of the alluvial-diluvial fan, which is located in the south of Zhangye Basin, including most Minle irrigated areas, the groundwater table depth are over 30m, most of which are more than 50m, and the groundwater is simple unconfined. Based on the recorded data of variations of groundwater from 1981-2000, an apparent decreasing trend is observed in some typical observed wells (Fig. 1). There into, annual decrease of the groundwater levels of Daman and Shigangdun Village, located in the center of fans, vary from 0.32m to 0.43m, adding up to 6.5-8.6m in 20 years. And in No. 65 observed well, located in Minle County, accumulative decrease of groundwater level is up to 12.91m, averagely 1m per year. These variations of the observed wells belong to markedly continuous decreasing types, which indicate that the groundwater levels of upper-middle areas of alluvial and diluvial fan in the southern basin keep on declining , and the higher the areas are located, the more the groundwater levels decline.

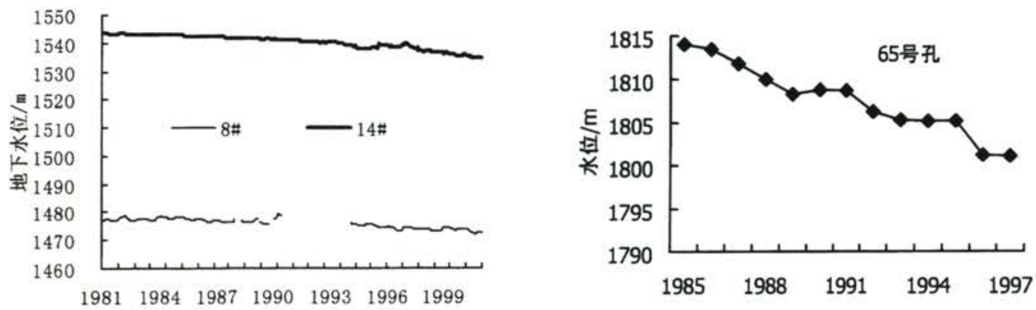



Figure 1 The long-term variations of groundwater levels in the upper-middle part of the alluvial and diluvial fan in Zhangye Basin

### 2.2 The trend of the long-term variations of groundwater levels in the lower part of alluvial fan

Most aquifers of he lower part of alluvial fan, located in the south and eastern Zhangye Basin, are simple unconfined, but in the north areas next to fine-grained-soil plain, there are multi-layer and confined aquifers. Generally, the groundwater level varied from 5m to 20m, mainly from 8m to15m. Due to sufficient and easily exploited, groundwater was largely exploited and mixed with river water to irrigate in this area. In general, the groundwater levels show a two phases variation trend (Fig.2A) in temporal distribution. In the decade of the 1980s the groundwater levels declined slowly with averagely 0.07-0.15m per year, even some parts had no change. In the 1990s, however, the groundwater levels in every part declined rapidly. In Yingke irrigated areas and Yangjia Village, for example, the groundwater table declined 4.2-6.5m. Long-term variations of groundwater in this area show the conversion from slow decrease to rapid decrease, which manifest a slow-rapid decreasing conversion type.

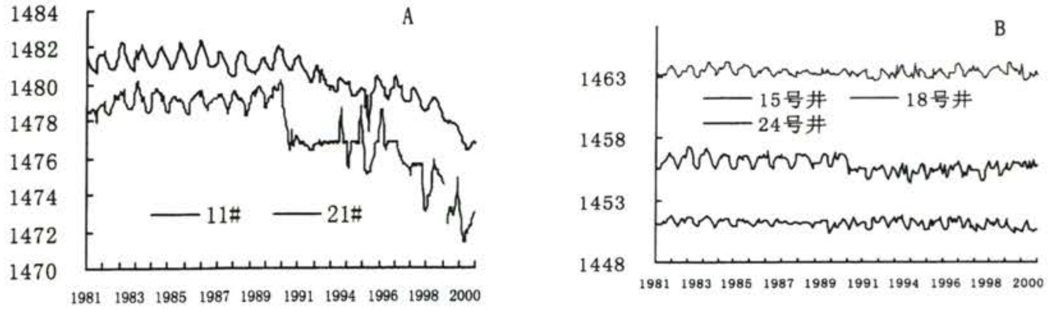



Figure 2 The long-term variations of groundwater levels in the lower part of alluvial fan and fine-grained soil plain

2.3 In the fine-grained soil plain in the centre of basin

The aquifers in the northern and northwestern Zhangye city, which are located in the center of Zhangye Basin, composed of multi-layers, are confined aquifers. Before the 1970s, this area was the main area where springs emerged, and local heads of confined groundwater were higher than the ground surface. Affected by the setup of confined groundwater the upper unconfined groundwater levels were relatively higher, part of which overflowed as spring water. At present, the groundwater table depths are usually lower than 2m in most of the area. The variations of groundwater levels are relatively stable (Fig. 2B) in this area, and in such local parts as the area from Xiaqin to Shandanhe Bridge they show an increasing trend after the 1998. Therefore, the groundwater level variation belongs to a stable type.

2.4 The trend of the long-term variations of groundwater levels in river valley plain of Linze and Gaotai county

In the alluvial valley along Heihe river in Linze and Gaotai County, main irrigated water comes from the river. In this area, the aquifer structure is complicated: the groundwater system is composed of multi-layer aquifers and the groundwater levels are usually less than 5m, most of them lower than 3m. According to the data of typical observed wells along the river, long-term variation characteristics of groundwater levels in this valley plain are shown in Figure 3. Similar to Zhangye fine-grained soil plain, the groundwater levels in this valley plain generally keep stable. In some local areas, such as the intersection of Liyuan River alluvial fan with Heihe river valley in Linze county, lower parts of Heihe river valley in Gaotai county, the groundwater level increase gradually from 1995-1997. There fore, the groundwater levels variation in this area belongs to a stable-increasing type.

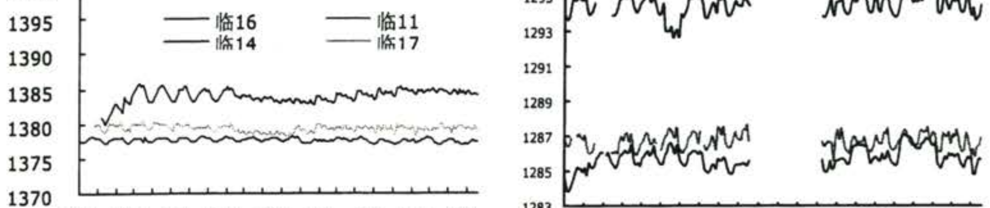



Figure3 The long-term variations of groundwater levels in Linze-Gaotai river valley plain

## 3. Spatial inter-annual variation characteristics of groundwater table

Inter-annual variations of groundwater tables are controlled by the type and structure of aquifers, the recharge and discharge of groundwater. The long-term variation type of groundwater table are formed and influenced by the inter-annual variation characteristics within regions share the similar types and structures of aquifers. Therefore, inter-annual variation characteristics of groundwater table are discussed according to the distributed areas of long-term groundwater table variations.

3.1 Inner-annual variations of groundwater tables in the continuous declining areas

Because of the deep storage, the recharge of groundwater comes from lots of infiltration of river water, so it is weakly affected by irrigated water but strongly affected by river water. Commonly, the higher groundwater levels appeared between August and next January, and the lower ones appear between March and July inner year before 1992, and compared to river flow the groundwater levels fluctuation have some time delayed (Fig.4 No.34 observed well). With the distance away from the river, the moments when the higher groundwater levels appear differ: the longer the distance is the longer it delays. Originally, the characteristics of groundwater table fluctuation are controlled by the hydrological process of river. However, the types of groundwater table variation inner annual changed from river hydrological process controlled to exploitations controlled types after 1992 (Fig.4 No.34 observed well). Since 1992, the higher groundwater levels appear between October and next March while non-exploitation period, and the lower ones appear between April and September during exploitation.

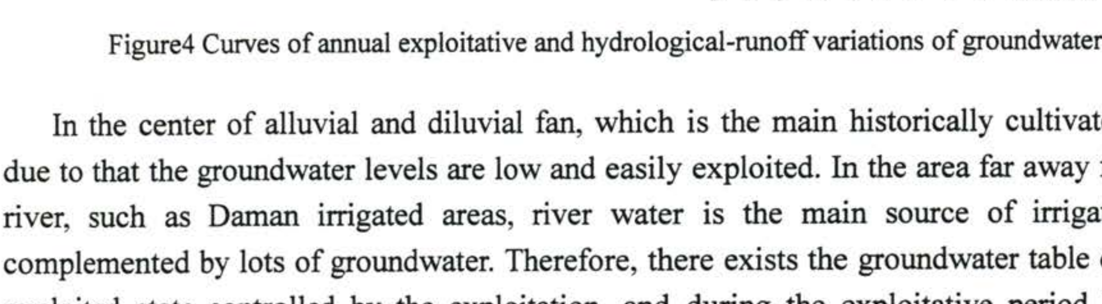



Figure4 Curves of annual exploitative and hydrological-runoff variations of groundwater

In the center of alluvial and diluvial fan, which is the main historically cultivated lands due to that the groundwater levels are low and easily exploited. In the area far away from the river, such as Daman irrigated areas, river water is the main source of irrigation but complemented by lots of groundwater. Therefore, there exists the groundwater table dynamic exploited state controlled by the exploitation, and during the exploitative period between April and September there is a low-groundwater-level while the non-exploitation period between October and next February there is a high-groundwater-level (Fig.4 No.6 observed well). The variations of groundwater in this area are uniform, and the variation range is within

0.44-1.97m. Annual variations of various typical years in this area as shown in Figure 4 (No.6 observed well) indicate that their characteristics have few change but the range of groundwater levels increases in two decades.

3.2 Variations of inner-annual groundwater table fluctuation in the slowly-rapidly decreasing conversion areas.

Inner-annual groundwater table fluctuation was complicated due to the infiltration of the river and irrigative water. Before and in the 1980s, regional inner annual variations of groundwater table were mainly controlled by the river hydrological and river water irrigative processes. Thereinto, hydrological-runoff type was mainly distributed in southern and western area near to Heihe riverbanks (Fig. 5, No. 11). In the 1990s, however, annual high groundwater levels appeared in October to next February, and the low groundwater levels were in April to September. These characteristics of groundwater table fluctuation belong to exploitation process controlled type (Fig. 5, No. 11).

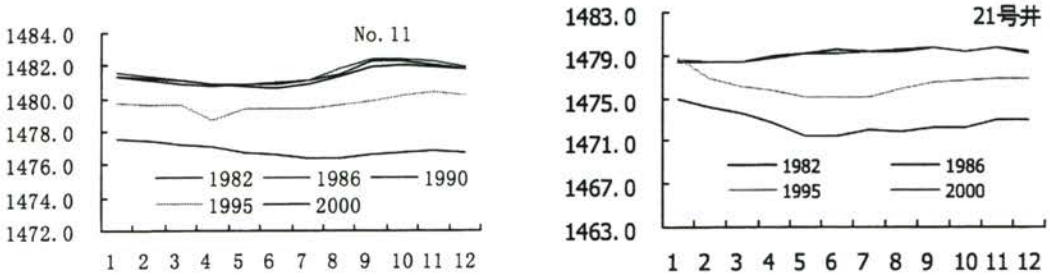



Figure 5 Curves of annual hydrological-runoff and irrigative variations of groundwater

The latter type, river water irrigative processes controlled the groundwater table fluctuation, was distributed in the most parts of lower alluvial fan. Before 1990, the variations of groundwater table, which were controlled by surface water irrigation, corresponded to the irrigative periods. In the irrigative period from April to November the groundwater kept high level, and in the non-irrigative period from December to March the groundwater kept low level (Fig. 5, No. 21). After the 1990, especially after 1995, the regional inner annual dynamic state of groundwater table changes remarkably. In the exploitative period from April to September regional groundwater levels commonly decline, and in the non-exploitative period from November to February higher groundwater levels emerge. The variation creates the relatively uniform exploitative type. Particularly, the original irrigative areas become the exploitative types after 1995.

3.3 Variations of inner-annual groundwater table fluctuation in the relative stable areas

On the background of long-term stable variations, this region contains the complicated inner annual variations of groundwater table. Deduced from inner annual variations in three representative observed wells (Fig. 6), it is clear that, before 1990, the groundwater table fluctuation type controlled by the river hydrological process is added to the basic irrigative one that is controlled by the irrigative factors of surface water. In the irrigative period from April to October groundwater levels are higher, at the same time, groundwater level peaks relating to the hydrological process of river appear in August to October. In addition, in some areas the variations of groundwater table show the exploitative characteristics in the irrigative period. In No. 25 and NO. 29 (Fig. 6), for example, the curves of variations of groundwater table fluctuation in June to August are apparently concave, the typical saddles. In general, the variation of groundwater table is irrigative-exploitative, partly irrigative-runoff. Since the 1990, however, with the exploitative factors augmenting, annual variations have invisible change. In NO. 29 well, for example, in the exploitative period from April to August the groundwater levels decline, and annual high groundwater levels appear in the non-exploitative period from November to February. The area represented by No. 25 and No.30 wells have still some characteristics of the irrigative-runoff type after 1990.

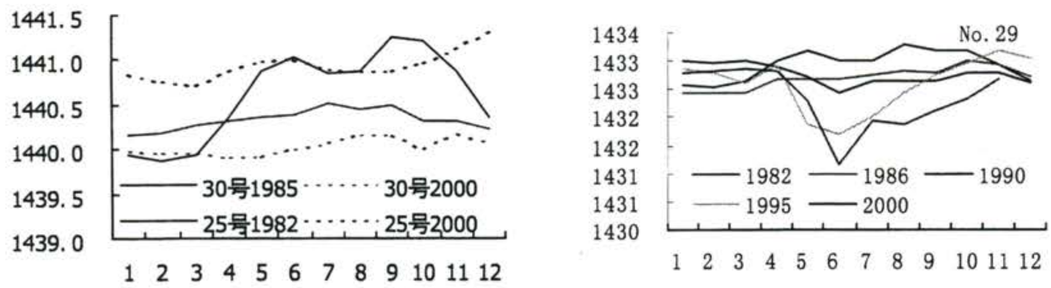



Figure 6 Mixed variations of groundwater

3.4 Variations of inner-annual groundwater table fluctuation in the stable-increasing areas

In the areas of valley plain along the river in Linze and Gaotai County, inner annual variations of groundwater are apparently controlled by the irrigative factors and hydrological factors of river together. From the beginning of irrigation in April, the groundwater levels keep on increasing, and attain the highest points in September to November (Fig.7). In the 1990s, the dynamic state of groundwater has such changes as the apparent return of groundwater levels in June to November since 1995, and annual high groundwater levels in December to February, which may be related to regional exploitation of groundwater. Generally, the groundwater table fluctuation in the river valley plain mainly exhibited irrigation factor controlled type together with some river hydrological process influence, and the fluctuation model has not obviously change through recent 20 years.

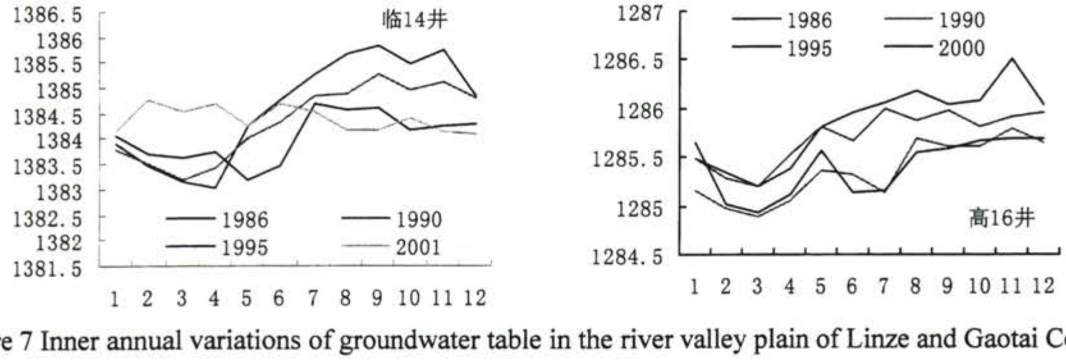



Figure 7 Inner annual variations of groundwater table in the river valley plain of Linze and Gaotai County

## 4. General variation of groundwater table depth in recent 20 years

Groundwater table depth is an important factor for the groundwater dependent plant, soil quality and groundwater irrigation and drinking conditions. Under the groundwater table variation, the depth varied with temporal-spatial series (Table 2). In the area of upper-middle of the alluvial-diluvial fan, the total groundwater table depth decreased by 5.5-12.9m in recent 20 years, which is the largest decrease of groundwater table in middle reach of Heihe river basin with decrease of 9.37m in average. Among that, however, the groundwater table deceased less in 1980s by average 2.6m, and another 6.7m decrease was taken place in 1990s. Inner annual fluctuation of groundwater table is about 1.37m, and keeps relatively stable during the recent 20 years in the upper-middle of the alluvial-diluvial fan (Table2).

Table 2 The temporal-spatial variations of groundwater table depth in recent 20 years

| | Upper-middle of the alluvial-diluvial fan | | Lower part of alluvial fan | | Fine-grained soil plain | | River valley plain | |
|---|---|---|---|---|---|---|---|---|
| | Annual | Inner annual | Annual | Inner annual | Annual | Inner annual | Annual | Inner annual |
| 1980s | 1.5-5.7 | 1.4 | -0.3-0.08 | 1.41 | -0.22-0.4 | 0.74 | 0.04-0.51 | 1.87 |
| 1990s | 5.2-7.3 | 1.35 | 2.83-6.69 | 2.33 | -0.32-0.43 | 0.55 | -0.67-0.05 | 0.86 |
| Total | 6.5-12.9 | | 2.92-6.73 | | -0.33-0.59 | | -0.31-0.23 | |
| Average | 9.37 | 1.37 | 4.74 | 1.87 | 0.22 | 0.65 | -0.002 | 1.36 |

Note: "+" means groundwater table decrease, and "-" means groundwater table increase.

In the lower part of alluvial fan, there were not visibly changes of the groundwater table in 1980s with the inner annual fluctuation of 1.41m. However, the groundwater table sharply decreased 2.83-6.69m in 1990s, and the inner annual fluctuation increased to 2.33m averagely. In whole, the groundwater table decreased averagely by 4.74m in recent 20 years (Table2). Under the relative stable-increasing types of long-term groundwater table variation, there were not some visible changes of groundwater table in the fine-grained soil plain and river valley plain with the average groundwater table variation only 0.22m and –0.002m respectively in recent 20 years (Table2). Inner annual groundwater table fluctuation was nearly as same as the upper-middle part of alluvial-diluvial fan in the river valley plain, inversely, the area of fine-grained soil plain have the least inner annual fluctuation of groundwater table.

## 5. Summary and discussion

In the middle reach of Heihe River, the variations of groundwater table which are influenced by the hydrology of river, irrigation and exploitation present various characteristics in different hydrological regions, as follows:

(1) In various physiognomy units different storage conditions result in remarkable distributions of variations of groundwater. From the top down in the alluvial and diluvial fans, the long-term variations of groundwater are the continuously rapidly decreasing, the

slowly-rapidly decreasing and the stable types, successively. In Linze and Gaotai valley plain in the middle reach, the variation of groundwater is stable-increasing. In the later two decades, in the fine-grained soil plain in the center of basin and its northern and western portions the interannual variations are stable, which reflects that the relationship between recharge and discharge of groundwater in this area presently keeps balance. In most southern basin the groundwater levels decline remarkably after the 1990s, which indicates that the relationship presents a negative balance and it intensifies gradually.

(2) Regional annual variations of groundwater are complicated and have the apparent temporal distributions. In the 1980s, in the simple unconfined aquifer districts of the upper-middle part of the fan, annual variations of groundwater are generally exploitative and hydrological-runoff. After the 1990s, the variations of groundwater are apparent: in the lower part of alluvial and diluvial fan and the fine-grained soil plain they turn to the exploitative and the irrigative, runoff-exploitative types, and in Heihe valley plain in Linze and Gaotai they turn to the irrigative-exploitative types. Only the simple unconfined aquifer districts in the upper-middle part of alluvial and diluvial fan have no change but the range of variations of groundwater levels increases.

(3) The former analysis indicates that in most parts of research regions the annual variations of groundwater turn to the exploitative types or exploitative-factors types, meanwhile, the human exploitative actions become the dominating factors influencing the variations of groundwater and lead to the changes of the inner annual variation types, such as the rapid decrease of groundwater levels in southern basin.

(4) Under the long-term variation of groundwater table, the depth of groundwater table decreased observably by average 4-10m in the upper-middle part and local lower part of alluvial and diluvial fan during recent 20 years. However, there are no visible decreases of groundwater table depth in the fine-grained soil plain and western river valley plain.

# Part 3: Evaluation The Impacts of Human Activity on Groundwater System with EIGT Model in Arid Zones of Northwest China

**Abstrct**: Precisely quantitative evaluation of the impacts of human activities on the regional groundwater system has great importance to the rational planning, management and utilization of groundwater resources and to the maintenance of the stability of the ecosystem depended on the dynamical variations of groundwater. Based on the groundwater dynamical data, the evaluation index of groundwater table (EIGT) model, which integrate the evaluating the extraction factor of groundwater dynamic change and the evaluating impacts of human activities on the relationship between river runoff, precipitation and groundwater, is presented in this paper. From the angle of the impacts of extraction factors on groundwater dynamical processes and the interrelation between surface runoff, precipitation and groundwater. The method evaluates the impacts of human activities on groundwater system and their temporal and spatial variation. Taking the Zhangye Basin in the middle reach of the Heihe River in northwest arid area of China as an example, the impacts of human activities on groundwater system in the past 20 years were evaluated. The results showed that since 1995 human activities have produced dramatic impacts on the basin's groundwater system and entirely altered the groundwater dynamics as well as its relation to the surface runoff and atmospheric precipitation in the mid-upper and lower parts of alluvial-diluvial fans, and local zones in the northern part of fine soil plain of the basin, however no evident impacts were imposed on groundwater system in the river valley plain in the western part of the basin. In addition, this paper also presents temporal-spatial variation of the impacts of human activities on groundwater system.

**Keywords**: Human activity, Groundwater System, Impact Evaluation, Evaluation Model, Heihe River basin

## Introduction

Ground water is an important part of the hydrologic cycle and has been a significant source of water to humanity since its beginnings (Alley et al., 1999). The growing demands on freshwater resources create an urgent need to link research with improved water management. Better monitoring, assessment, and forecasting of water resources will help to allocate water more efficiently among competing needs (Naiman, et al., 2001). Recently, the human actives, including water utilization and land use, are becoming a vital aspect which affects water system (both surface and ground) which in turn has a sever impact on the hydrological regimes and water supply in the world (Belousova, 2003; Alley et al., 1999). Human activities are intricately linked to the evolution and dynamics of groundwater quantity and quality. Given the alarming rate of land-use change globally, it is important to understand the linkages between land-use change and groundwater dynamics, as land use affects the quantity and chemical quality of recharge water (Gehrels, 2001; Querner, 2001). Each ground-water system and development situation is unique and requires an analysis adjusted to the nature of the water issues faced, including the social, economic, and legal constraints that must be taken into account. A key challenge for achieving ground-water sustainability is to frame the hydrologic implications of various groundwater exploitation and groundwater dynamics in such a way that they can be properly evaluated. With time, many issues involving the quantity, quality, and ecological aspects of surface water are interrelated with ground water. Thus, groundwater hydrologists are challenged continually by the need to provide greater refinement to their analyses and to address new problems and issues as they arise (Shah, et al., 2000; Alley et al., 1999).

The characteristics of water resources in arid zones determine that groundwater as a rule is the most important water resources and the best selection of water supply in arid zones. Generally, groundwater resources are the essential element to support the oasis ecosystem in arid zones and to maintain the socioeconomic development in desert regions (Mtembezeka, et al., 1997; Shah, et al., 2000). Globally, groundwater resources play a non-fungible leading role in solving water shortage problem in arid zones. Scientific assessment and effective management are an important guarantee and essential requisite for the better exploitation of groundwater resources in arid zones (Schwarts, et al., 2003; Khazai, 2001). Groundwater dynamic regimes reflect the formation and variation laws of groundwater, and they are mainly controlled by precipitation, surface water and groundwater extraction etc. The output of the response of groundwater system to the external disturbing impacts is an important information source for us to understand the impacts of human activities on the groundwater system (Sato, et al., 2003; Asmuth, et al., 2001). For this reason a dynamical monitoring network of groundwater was gradually established in most of irrigation regions in arid inland basins of China since 1970s (Hydrologic Bureau of WMC, 1995).

The groundwater level directly determines the natural dynamic behaviour of the groundwater system, and is (hence) often the most important information for groundwater systems management (Ni, et al., 2001). The research of the dynamical changes of groundwater and their affecting factors provides a scientific basis for working out a basin's wateruse planning, agricultural arrangement, irrigation and draining waterlogged areas, control salinization, water resource evaluation and management, and environmental protection (Belousova, 2003; Asmuth, et al., 2001; Xu, 2003). At present, many countries have used the dynamical observation data of groundwater to evaluate the degree of the impact of human extraction activity on groundwater system. In this respect there are two evaluation methods. First, directly using the dynamical variation trend of groundwater to make a qualitative judgment, or making a comparative analysis using the mean water table, maximum water table and minimum water table of a season in a year (Asmuth et al., 2001; Xu, 2003; Khazai, 2001), such method is simple but is not precise and quantitative. Second, mathematical models are used to make quantitative evaluation, such as statistical regression model, response matrix model and groundwater level numerical model etc (Bierkens, et al., 1999; Knotters and Walsum, 1997; Asmuth et al., 2001), this method requires a number of parameters and some hydro-geologic assumption conditions, and hence it is quite complex and inconvenient. Based on the dynamical data of groundwater level, and the interaction of groundwater, surface water and atmospheric precipitation, this paper establishes the EIGT (Evaluation Index of Groundwater Table) model, a corresponding indexes and mathematic model and puts forward a simple integrated evaluation method. This method is used to evaluate the impacts of human activeities on the groundwater system in the middle reach of the Heihe River, northwest China, and thereby provides a basis for working out the comprehensive rehabilitation planning of the Heihe River basin.

## 1. Study region and Methodology

### 1.1 Study region description and evaluation zoning

The middle reach of the Heihe River—the second largest inland river of China was selected as the study region, which belong to Zhangye Basin in topographic division. It is located in the middle section of the Hexi Corridor, between 97°20′~102°13′E and 37°28′~39°59′N, with a land area of 4214 million $hm^2$ (Fig. 1). The research region has a typical temperate continental climate, mean annual precipitation varies between 60~280 mm, annual evaporation 1000~2000 mm. The mountain-originating river, Heihe River, is the only surface runoff of the Zhangye Basin. Since 1951 no obvious changes in surface runoff and atmospheric precipitation were observed in the region, or roughly kept stable (Zhang, et al., 2003). The topography in the region dips from southeast to northwest, with a slope of 25-4‰. Geomorphologially, the southern part is the piedmont alluvial, alluvial-diluvial Gobi plain and the middle part of the basin is alluvial-diluvial fine soil plain. Owing to the limitation of landform, deposits and tectonic conditions groundwater mainly comes from Quaternary interstitial water. From the southern piedmont to the northern basin centre the aquifer consists of single unconfined aquifer transiting to multilayer confined aquifer, and the groundwater table gradually becomes shallow to reach the spring overflow zone (Gao and Li, 1990; Wang and Cheng, 1999). According to landform, aquifer structure, groundwater storage and groundwater use conditions the study region was divided into four subzones. The extents and location are shown in Figure 1, and the climatic and hydrogeologic conditions, irrigation water sources and observation points of the four subzones are presented in Table 1.

The exploitation of groundwater resources in the Zhangye Basin has a history of nearly 200 years, however, as a whole, its consumption amount was small before 1970s. Since 1980s onwards the region's groundwater was extensively exploited. The temporal variations of groundwater extraction and the spatial distribution of extraction intensity in the zhangye Basin in the past 20 years are presented in Table 2. During the 10-year period of 1980-1989 the region's mean annual extraction volume of groundwater was 60 million $m^3$, starting from 1990s its extraction volume increased rapidly, the extracted volume in 1999 was 2 times the mean volume of the first five years of 1990s and 6 times the mean volume of 1980s. The extraction intensity of groundwater is different from place to place, the mid-upper part of alluvial-diluvial fans in the southern part of the basin has a relatively low extraction intensity, belonging to slight extraction zone, the lower part of the alluvial-diluvial fans have the largest extraction intensity, belonging to intense extraction zone; fine soil plain and river valley plain in the western part of the basin have an extraction intensity ranging from 3.0-25.0 $\times$ $10^4 m^3/km^2.a$, belonging to moderate extraction zone.

1.2 The quantity evaluation method of EIGT model

In most occasions, human activities, including land use and water resources utilization (both surface water and groundwater), have integrated affections on groundwater system, which impact on the groundwater dynamics and recharge of groundwater system. Based the groundwater dynamic changes and the relationship between groundwater dynamic and recharge factors, normally the river runoff and precipitation, the evaluation index of groundwater table (EIGT) model, which is an integrated method used to evaluated the degree and characteristics of human activities affection on groundwater system, is set up by quantifiable index. The method combines two fields of groundwater dynamic evaluation modeling. Firstly, the exploitation index model based on the comparing the annual groundwater dynamic with exploitation season groundwater dynamic is used to evaluate the affection of extraction factor on groundwater system. Secondly, the runoff and rainfall index model is set up to evaluate the affections of human activities on groundwater recharge system. The way in which the each model is carried out is described below.

1.2.1 Exploitation index evaluation modelling

Groundwater dynamical types in arid zones generally included three types (Cheng and Qu, 1992; Gao and Li, 1990) (Fig.2): (1) Runoff hydrological type: dynamical changes of groundwater are closely related to the changes in river runoff and precipitation processes and exhibit an interrelated dynamical processes of river hydrology and precipitation changes; (2) Irrigation type: the dynamical changes of groundwater are controlled by irrigation, groundwater table during irrigation period is in a high water-table interval; (3) Extraction type: the dynamical changes of groundwater are controlled by extraction activity, during extraction period the groundwater system is in a low water-table interval. The main difference in the various groundwater dynamic of runoff type, irrigation type and extraction type is manifested in the water table changes during the irrigation and extraction periods (from June to September) (Fig.2). For runoff hydrological type, the higher groundwater levels appeared between August and November, and it appeared between May and November for irrigation type. If the groundwater table dynamic changed to extraction type under human exploitation, however, the periods between May and September are the low water-table interval. In order to quantitatively evaluate the degrees of the impacts of extraction factors on the groundwater systems in various hydrogeologic units a measuring factor of extraction index, which is based on the relative water table range, is introduced. It is defined as:

$$\delta_t = (\Delta H_{pt} / H_t)\mu \qquad (1)$$

Where $\delta_t$ is the index of extraction factor of the calculated year (the t year), dimensionless; $\Delta H_p$ is the difference between the mean monthly water table elevation from June to September of the calculated year in specified region and the mean water table elevation of current year, $\Delta H_{pt} = H_t - H_p$; $H_t$ is the mean annual water table elevation in specified region or at typical well points. Reference year t may be ages, such as 1980s and 1990s etc. $\mu$ is a systematic constant, it is determined by the magnitude of the elevation of groundwater table. In this study region the elevation of groundwater ranges from 1000-2000m, hence

$\mu$ =1000.

The evaluation criterion of the intensity of the extraction index is: ①$\delta_t \geqslant 0.2$, several affected. The dynamical change of groundwater is controlled by human exploitation, and it was dominated by extraction dynamic type. ②$0.1 \leqslant \delta_t < 0.2$, moderately affected. Extraction activities have a certain influence on the groundwater dynamics, and groundwater dynamic partly reflect the extraction type. ③$0.0 \leqslant \delta_t < 0.1$, slightly affected. Extraction activity has a slight influence on the groundwater dynamical changes, and groundwater dynamics exhibit a weak extraction character. ④$\delta_t < 0.0$, no effect or no extraction activity. Groundwater dynamics keep original and intact type.

1.2.2 Runoff and precipitation index evaluation modelling

The increased extraction intensity will significantly alter the dynamical type of groundwater and thereby inevitably affect the interrelation between the recharge elements of groundwater, including surface runoff and precipitation. Under the conditions that surface runoff and precipitation keep relatively stable for recent 50 years, the changes in the interrelation between surface water, precipitation and groundwater caused by the variations of groundwater dynamical types are mainly attributed to the impacts of human activities. In order to quantitatively evaluate the degree of the impact of human activities on the relation between surface runoff, precipitation and groundwater, the runoff and precipitation index are introduced and they are expressed as:

$$\gamma_t = \frac{|H_t - f(R_t)|}{H_t} \times \beta, \quad f(R_t) = H(R_t) \pm \varpi, \quad R_t \text{ is relatively stable} \qquad (2)$$

$$\rho_t = \frac{|H_t - f(P_t)|}{H_t} \times \alpha, \quad f(P_t) = H(P_t) \pm \sigma, \quad P_t \text{ is relatively stable} \qquad (3)$$

Where, $\gamma_t, \rho_t$ are the runoff index and precipitation index respectively. $H(R_t), H(P_t)$ are the statistical relation functions of surface runoff, precipitation and groundwater established by the data series unaffected by human activities; $\varpi, \sigma$ are the standard residual variances of statistical function of surface runoff, precipitation and groundwater. $\beta, \alpha$ are the proportional constants. According to the magnitude of groundwater table $H_t$ may select 10, 100 or 1000. $R_t, P_t$ are the surface runoff and precipitation in the calculated period.

The evaluation criteria of runoff indexes and precipitation indexes are as follows: ①$\gamma_t <$ 0.1, there is no significant influence; ②$0.1 \leqslant \gamma_t \leqslant 0.5$, there is a slight influence; ③$0.5 < \gamma_t \leqslant 1.0$, there is a moderate influence; ④$1.0 < \gamma_t \leqslant 2.0$, there is severe influence; ⑤$\gamma_t \geqslant 2.0$, there is a very severe influence. The larger the index, the weaker the influences of surface runoff or precipitation on the groundwater dynamics are.

1.3 Analytical data basis

The evaluation requires the monthly mean values of groundwater dynamical observations, atmospheric precipitation, and surface runoff at representative stations of the region. The data sources used in this study includes: (1) groundwater dynamical observation data: a total of 54 observation wells were arranged in the Zhangye Basin of the Heihe River, 28 of which were started to be observed in 1980, available data include the monthly mean values in 20 years from 1981 to 2000; another 28 wells were started to be observed in the second half of 1983, available data include the monthly mean values in 17 years from 1981 to 2001. (2) Precipitation and surface runoff: the monthly mean precipitation data recorded at Zhangye and Gaotai weather stations in the study region were used, the surface runoff data include the monthly mean discharge values observed at the Yinluoxia Hydrologic Station at the mountain out mouth of the Heihe River and the discharge values observed at the Zhengyixia Hydrologic Station at the downstream outlet of the Basin.

## 2. Evaluation of extraction impacts on the groundwater dynamical changes

The groundwater dynamical observation wells were unevenly arranged in various evaluation subzones, at least more than 3 wells were selected for the observation. According to equation (1) the indexes of groundwater dynamical extraction indexes at typical well points were calculated and their results are presented in Table 3. Then, according to the above-mentioned evaluation criteria the degrees of the impacts of the extraction factors in different periods in various subzones in the Zhangye Basin were made and their results are presented in Table 3.

Since the 1980s, the index of extraction factors has been larger than 0.2 (Well No. 6 and 8 in table 3) in most of the mid-upper part of alluvial-diluvial fan in the southern part of the basin, this shows that in the past 20 years human exploitation of groundwater has seriously affected the groundwater dynamics in the region. As a result, the groundwater dynamics clearly appear as extraction type (Figure 3a), i.e. it is in a low water-table interval during the extraction period between April and September, and is in high water-table interval during the non-extraction period between November and March.

At the lower part of alluvial-diluvial fan in the center of the basin, human extraction activity did not affect the groundwater dynamics prior to 1990 for the extraction index was less than 0 in most area of the region, therefore, groundwater dynamics remained its natural types, which were dominated by river hydrologic type and irrigation type (Figure 3b). However, after 1990, especially after 1995, the measuring factors of extraction degree has been exceeding 0.2 in most of the region, suggesting that human exploitation of groundwater has seriously affected and gradually controlled the groundwater dynamics. As a result, the groundwater dynamical type in the region gradually changed into extraction type from original hydrologic runoff type and irrigation type. The transformation of groundwater dynamical types is closely related to the indexes of extraction factors.

In the past 20 years the extraction indexes of groundwater dynamics in most of the fine soil plain in the center of the basin and its northern part were smaller than 0.1, the groundwater dynamics was not significantly affected by human extraction activities and was mainly controlled by the recharge sources of groundwater (well No. 1 in Figure 4a). However, since 1990 the measuring extraction index in the northern part of the fine soil plain dramatically increased, during the 1990-1995 period it experienced a moderate degree of extraction disturbance, and from 1995 onwards the measuring extraction index was generally larger than 0.2, the groundwater dynamics obviously appeared as extraction type controlled by extraction activities (No. 29 curve in Figure 4a). In the past 20 years the extraction index in the river valley plain of Linze and Gaotai, that are a part of the fine soil plain in the northwest of the basin, has always been smaller than 0.1, human extraction activity did not affect the groundwater dynamics in the region (Figure 4b).

The extraction indexes quantitatively reveal the degree of the impacts of human extraction activity on the groundwater dynamics in different regions. As for the Zhangye Basin the extraction index of 0.2 can be viewed as a critical value to judge whether human extraction activity has altered the groundwater dynamic type. Since 1990s the annual dynamical type of groundwater in the lower part of alluvial-diluvial fans and the northern part of fine soil plain has tended to evolve into extraction type, and in local places it has already turned into extraction type since 1995; during the 20-year period since 1980s the annual dynamical type of groundwater in the mid-upper part of alluvial-diluvial fans has turned into extraction dynamical type, which was controlled by extraction activity; however, in the river valley plain in the western part of the basin human extraction activities have not evidently affected the groundwater dynamical changes.

**3. Evaluating the impacts of human activities on the relationship between surface**

**runoff, precipitation and groundwater**

3.1 The relationship of $H(R_t), H(P_t)$ and their change

Using the statistic regression method, the statistic relation function between precipitation and groundwater table elevation ($H(P_t)$) and the relation function between river runoff and groundwater table elevation ($H(R_t)$) are established for various subzones and listed in Table 4, Table 5 and Table 6 respectively.

In the lower part of alluvial-diluvial fans the groundwater table depth is relatively shallow, surface water (including river water and irrigation water) and precipitation have significant influences on the groundwater dynamics as compared to the mid-upper part of alluvial-diluvial fans, and there were two groundwater dynamical types, irrigation type and river hydrologic type. As for $H(P_t)$ of these two dynamical types in the region, they are characterized by similar function form and variations. Prior to 1990 the $H(P_t)$ have a weaker quadratic parabolic curve with statistical correlation coefficient was 0.57 or so (Table 4). However, such statistical relationship no longer existed after 1990. During 1980s groundwater dynamical change was closely related to river runoff processes in the river hydrologic type of groundwater dynamic zone, there were positive relationship between runoff and groundwater table elevation, and the $H(R_t)$ have logarithmic curve no matter it is close to or far away from the river channel with the correlation coefficient R 0.78 or so (Table 4). Irrigation type of groundwater dynamic is widely distributed in the old oases at the lower part of alluvial-diluvial fans, since the early 1980s the irrigation type of groundwater dynamical types have been formed due to the effects of irrigation factors, but it has been found that there still existed a certain positive correlation between groundwater table and river runoff; groundwater table exhibited an approximate logarithmic curve change with the river runoff, and the correlation coefficient R was 0.65 or so (Table 4). During 1990s, especially since 1995, the relationship no longer existed both river hydrological type zone and irrigation type zone.

In the fine soil plain in the center of the basin and its northern part the groundwater table depth is less than 10 m, aquifer structure is complex and there is confined water in most of the region. In the 1980s there were three groundwater dynamical types i.e. river hydrologic type, irrigation type and mixed irrigation-runoff type. The river hydrologic dynamical type mainly occurred in the vicinity of the river, there was an relatively positive quadratic parabolic curve correlation between the precipitation and groundwater table (R=0.66) (Table 5), and it was a region that the precipitation had the most significant influence on the groundwater dynamics in Zhangye basin. There was a quite significant correlation between surface runoff and groundwater dynamics in the region, groundwater table exhibited a positive logarithmic curve with the changes in surface runoff (R=0.89), it manifested that surface runoff played a control role to the groundwater dynamical changes (Table 5). After the 1990s, the correlation between precipitation and groundwater table no longer existed, and the correlation between surface runoff and groundwater table dramatically changed into a weaker quadratic parabolic curve (R=0.57). Irrigation runoff type is a mixed river hydrologic type and irrigation type of groundwater dynamics, it mainly occurs in the eastern and northeastern part of the region. Precipitation has a weak influence on the groundwater dynamics. During 1980s the region's surface runoff had a quite obvious relation to the groundwater dynamics with a positive logarithmic curve (R=0.8). After 1990s, the relation between surface runoff and groundwater table became weaker but still maintained a positive logarithmic curve (R=0.61) (Table 5).

In the mid-upper part of alluvial-diluvial fans in the southern part of the basin, the groundwater table depth is more than 30m, so that the precipitation has little relation to the groundwater dynamics. Prior to 1990, the region's groundwater dynamics had a better correlation with surface runoff (R=0.67) (Table 6), this showed that at that time the groundwater dynamics was significantly affected by the river runoff. However, during the 10-year period after 1990, surface runoff almost showed no relation to groundwater dynamics. The river valley plain, located in the downstream interior basin in the western part of the region, has a groundwater table less than 10m. During the 1980s groundwater table showed a close correlation with surface runoff (R=0.75) (Table 6). But such correlation no longer existed in 1990s. Owing to lower precipitation of less than 100 mm, precipitation shows little relation to the groundwater dynamics.

### 3.2 Evaluation results of runoff index and precipitation index

The runoff indexes and precipitation indexes in different zones and different subzones of groundwater dynamical types were calculated using the statistical regression equation listed in the Table 4-6, equation (2) and (3), and the results are shown in Figure 5.

The runoff indexes in the fine soil plain were small and relatively stable before 1995, but their seasonal amplitudes were large with the difference by 5 times or even 13 times (Fig.

5a). High values generally occurred between May and August, while low values occurred between December and February. During the 1990-1995 period, the runoff indexes in the subzones of river hydrologic type, irrigation type and extraction type were 0.073, 0.119 and 0.069 respectively (Table 7). From 1996 onwards the runoff indexes in the fine soil plain significantly increased, especially in the subzones of the river hydrologic type and irrigation type subzones the extraction runoff indexes increased to 0.152 and 0.176 respectively, or a 2-3 fold increase (Table 7). This showed that after 1995 human extraction activities evidently affected the relation between groundwater and surface runoff in the region. In the subzones of irrigation type and river hydrologic type groundwater and precipitation had a better correlation, of which the precipitation indexes in the river hydrologic type subzone were 0.084 and 0.139 before and after 1995 respectively, further they increased significantly after 1995. In the irrigation type subzone the precipitation indexes changed little before and after 1995, they were 0.108 and 0.101 respectively and were significantly larger than those in the river hydrologic type subzone. As a whole, the extract activities in the fine soil plain only have a slight influence on the relation between surface runoff, precipitation and groundwater table.

Runoff indexes in the lower part of alluvial-diluvial fans in Zhangye Basin were large, with large inter annual range (Fig. 5b). During the 1990-1995 period, the annual mean runoff indexes value in the subzone of river hydrologic type varied between 0.12-0.59, implying a slight degree of influence. The corresponding figure in the subzone of irrigation type ranged from 0.45-1.48, implying a moderate degree of influence (Table 7). After 1996, however, the runoff indexes increased rapidly, in the subzone of river hydrologic type they increased by 0.83-2.3, or averaged 1.63, belonging to severely affected area. The corresponding figures in the subzone of irrigation type were 1.26-4.3, averaged 2.55, belonging to very severely affected area (Table 7).

In the mid-upper part of alluvial- diluvial fans in the basin the runoff indexes and their inter-annual variations were large too (Figure 5c). During the 1990-1995 period, the mean annual runoff indexes varied between 0.24-1.26, belonging to moderately affected area. After 1995 the runoff indexes increased linearly, and reached 0.83-3.7 during the 1996-2000 period, averaged 2.11 (Table 7). This shows that since 1995 the extraction activity has seriously affected the region's relationship between groundwater dynamics and river runoff. Relatively, the extraction runoff indexes in the downstream river valley plain were small and tended to become stable in the past 20 years, with small inter annual variations (Figure 5c). The runoff indexes during the 1990-2000 period varied between 0.19-0.17 and showed no significant variation before and after the 1995. The mean annual runoff index was 0.181, belonging to slightly affected area (Table 7).

## 4. Conclusion

(1) Based on the groundwater dynamical observation data, the EIGT model is put to quantitatively evaluate the impacts of human activities on the groundwater system. Integrating the extraction index and runoff and precipitation index, the method could reveal the degree of human activities' impacts on groundwater dynamics and the relationship between river, precipitation and groundwater. Taking account the spatial hydro-geological subzones and the variation of groundwater dynamics, the EIGT model results is a spatial component to time series of affection assessment.

(2) The impact of human activity on the groundwater system in middle reaches of Heihe river basin northwest China, as an example, was evaluated using the EIGT model. The results reveal an evident temporal and spatial differentiation character of the impacts degree of human activities on groundwater system. In the past 20 years the groundwater extraction intensity has being enhanced up since 1995 and specially in the lower parts of alluvial-diluvial fans and the fine soil plain in the middle reach of the Heihe River, and it have seriously affected the groundwater system in the upper to lower parts of alluvial-diluvial fans; the occurrence and development of single extraction dynamical type of the groundwater system as well as the changes in the influences of surface runoff and precipitation on groundwater revealed that a large regional cone of depression has formed in the region; extraction activities also started to significantly affect the groundwater system in local places of the fine soil plain (especially its north part), however no evident variations were observed in the river valley plain in the western part of the basin.

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Table 1 Natural conditions, hydrogeologic settings and observation points in the study region

| subzone | extent and natural condition | hydrogeologic features and irrigation condition | observation points |
|---|---|---|---|
| Mid-upper part of alluvial-diluvial fans | Located in piedmont alluvial and diluvial gobi plain in the south, 1500-2800m in elevation, annual precipitation 120-300mm. | Single unconfined aquifer, groundwater table depth> 30m; irrigation is dominated by river water, local places are irrigated by river water and well water. | No. 6, 8 and 14 |
| Lower part of the alluvial and diluvial fan | Intersection of alluvial and diluvial Gobi plain with the fine-grained soil plain with elevation between 1400-1800m and the annual precipitation of 100-250mm. | Conversion from single unconfined aquifer to multi layer confined aquifer with the water table depth between 8-30m; irrigated by well water mixed with river water. | No. 3, 4, 5, 11, 13 and 21 |
| Fine-grained soil plain | Located in Zhangye city area of the fine-grained soil plain with elevation between 1300-1600m and precipitation of 100-150mm. | Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation. | No. 1, 2, 18, 15, 25, 28, 29 and 30 |
| River valley plain in the lower part of basin | River valley alluvial plains along the rivers in Linze and Gaotai, northwestern part of the fine soil plain, 1270-1500m in elevation, annual precipitation 60-120mm. | Multi layer confined aquifer with water table depth less than 10m, ground water, spring and river water mixed for irrigation . | No. L11~23, G1~3, G8~16 |

Table 2 Extracted volume of groundwater and the distribution of extraction intensity in Zhangye Basin

| Extracted volume of groundwater ($10^8m^3/a$) | | | | Distribution of groundwater extraction intensity ($10^4m^3/km^2.a$) | | | |
|---|---|---|---|---|---|---|---|
| 1980s | 1990-1995 | 1997 | 1999 | Mid-upper alluvial-diluvial fan | Lower alluvial-diluvial fan | Fine soil plain | River valley plain in lower part |
| 0.6 | 1.951 | 2.254 | 3.69 | 2.9-12.37 | 13.7-61.2 | 3.87-15.7 | 2.73-25.4 |

Table 3 Measuring factors of groundwater extraction degrees and variations in different hydrogeologic units in the middle reach of the Heihe River

| Mid-upper part of alluvial-diluvial fans in the southern part of the basin | | | | | | Lower part of alluvial-diluvial pans in the center of the basin | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Well No. | 1982 | 1986 | 1990 | 1995 | 2000 | Well No. | 1982 | 1986 | 1990 | 1995 | 2000 |
| 6 | 0.46 | 0.24 | 0.28 | 0.11 | 0.53 | 11 | -0.02 | -0.02 | 0.07 | 0.09 | 0.25 |
| 8 | 0.38 | 0.28 | | 0.27 | 0.28 | 21 | -0.20 | -0.24 | -0.14 | 0.44 | 0.57 |
| 14 | 0.11 | 0.06 | 0.08 | 0.26 | 0.23 | 13 | -0.05 | -0.11 | -0.02 | 0.28 | 0.21 |
| Evaluation | Continuously and severely affected areas | | | | | Evaluation | Slightly-severely affected areas | | | | |

| Fine soil plain in the center of basin and its northern part | | | | | | River valley plain in the western part of the basin | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Well No. | 1982 | 1986 | 1990 | 1995 | 2000 | Well No. | 1985 | 1990 | 1995 | 2000 |
| 25 | -0.27 | -0.07 | -0.02 | 0.06 | 0.02 | L12 | -0.55 | -0.35 | -0.22 | 0.00 |
| 29 | -0.13 | -0.04 | 0.12 | 0.26 | 0.40 | L14 | -0.19 | -0.11 | 0.06 | 0.07 |
| 30 | 0.15 | -0.09 | -0.04 | 0.02 | -0.05 | G7 | -0.26 | -0.24 | -0.16 | -0.17 |
| 1 | -0.24 | -0.07 | -0.11 | 0.00 | -0.15 | G 16 | -0.17 | -0.07 | 0.03 | -0.13 |
| Evaluation | No influence-slightly affected areas | | | | | Evaluation | No influence | | | |

Table 4 $H(R_t), H(P_t)$ and their variations in the lower part of alluvial-diluvial fans in the basin

| Sub-zone | $H(P_t)$ | | $H(R_t)$ | |
|---|---|---|---|---|
| | 1980s | 1990s | 1980s | 1990s |
| Hydrologic runoff type | y = -0.0002x$^2$ + 0.03x + 1481.2, R = 0.57 | No significant relation | y = 0.4707Ln(x) + 1479.7, R = 0.78 | No significant relation |
| Irrigation type | y = -0.0003x2 + 0.0313x + 1478.8, R = 0.57 | No significant relation | y = 0.3479Ln(x) + 1477.8, R = 0.65 | No significant relation |

Table 5 Relations between groundwater dynamics with precipitation and surface runoff in the fine soil plain in the center of the basin and its northern part

| Subzone | Relation between atmospheric precipitation and groundwater table | | Relation between surface runoff and groundwater table | |
|---|---|---|---|---|
| | 1980s | 1990s | 1980s | 1990s |
| Hydrologic runoff type | y = -6E-05x$^2$ + 0.011x + 1440.3, R = 0.66 | No significant relation | y = 0.187Ln(x) + 1439.7, R = 0.89 | y = 4E-06x$^2$ + 0.001x + 1440.1, R = 0.57 |
| Irrigation type | y = -3E-05x$^2$ + 0.005x + 1433.6, R = 0.56 | No significant relation | y = 0.0757Ln(x) + 1433.4, R = 0.69 | no significant relation |
| Irrigation runoff type | y = -4E-05x$^2$ + 0.011x + 1463.4, R = 0.41 | No significant relation | y = 0.317Ln(x) + 1462.3, R = 0.79 | y = 0.2056Ln(x) + 1462.5, R = 0.61 |

Table 6 Interrelations between groundwater dynamics, surface water and precipitation and their variations in the lower part of alluvial-diluvial fans in the basin

| subzone | relation between atmospheric precipitation and groundwater table | | relation between surface runoff and groundwater table | |
|---|---|---|---|---|
| | 1980s | 1990s | 1980s | 1990s |
| mid-upper part of alluvial-diluvial fans in the basin | y = -0.0001x$^2$ + 0.031x + 1470.6, R = 0.412 | no significant relation | y = 0.7439Ln(x) + 1468.2, R= 0.67 | no significant relation |
| river valley plain in the western part of the basin | no significant relation | no significant relation | y = 0.3849Ln(x) + 1285.3, R = 0.75 | no significant relation |

Table 7 Extraction runoff indexes in different subzones of hydrogeologic units and the variations in different periods

| | Mid-upper part alluvial-diluvial fans | Lower part of alluvial-diluvia fan | | Fine soil plain and its northern part | | | Downstream river valley plain |
|---|---|---|---|---|---|---|---|
| | | Hydrologic type | Irrigation type | Hydrologic type | Irrigation type | Extraction type | |
| 1990-1995 | 0.712 | 0.382 | 1.06 | 0.073 | 0.119 | 0.069 | 0.193 |
| 1995-2000 | 2.11 | 1.633 | 2.55 | 0.152 | 0.112 | 0.176 | 0.169 |
| 1990s | 1.46 | 0.91 | 1.85 | 0.116 | 0.115 | 0.127 | 0.181 |

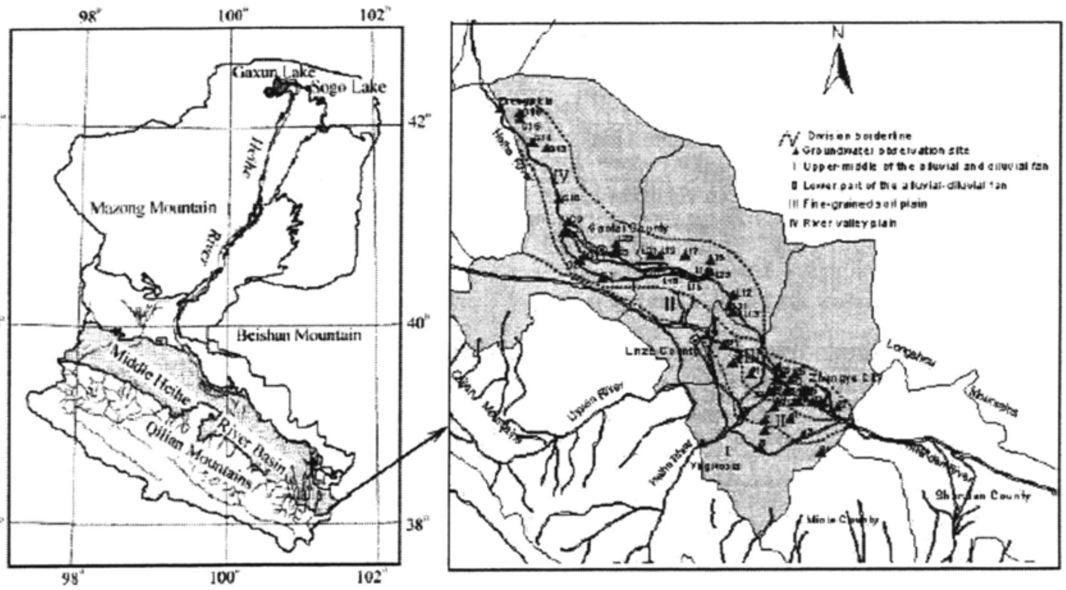


Figure 1 The Diagrammatic map of study area, observation points distribution and sub-zones

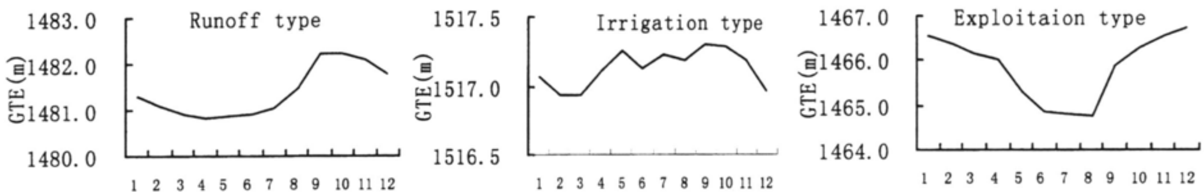


Figure 2 Three main groundwater dynamic types in study area

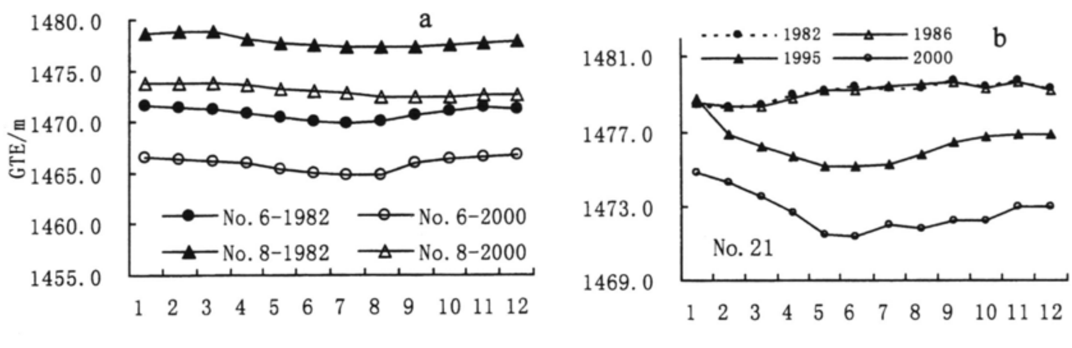


Figure 3 Dynamical changes of groundwater in the mid-upper (a) and lower alluvial-diluvial fans (b) in the basin

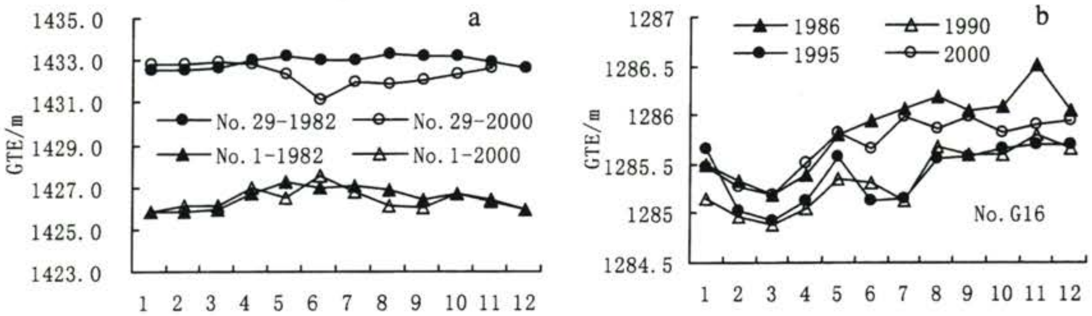


Figure 4 Characteristics of groundwater dynamical changes in the fine soil plain (a) and river valley plain (b)

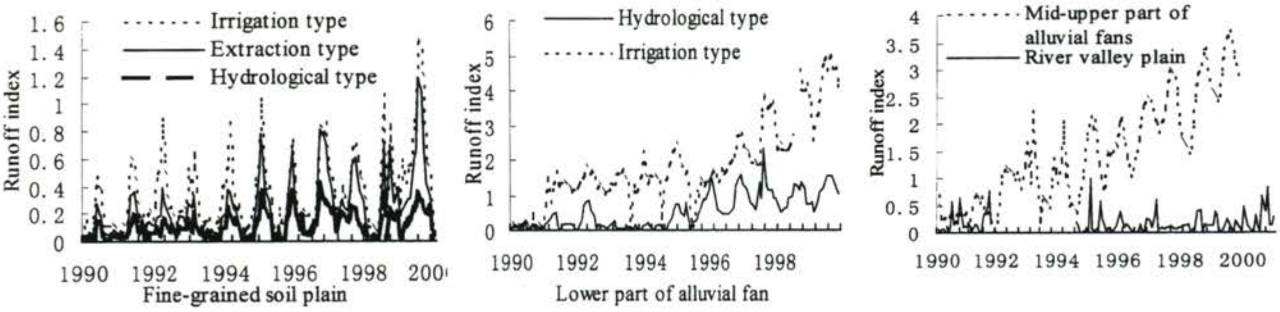


Figure 5 Variation courses of runoff indexes in different evaluation subzones in the Zhangye Basin in the Heihe River basin

# Part 4: The groundwater resources change and its cause analysis in the middle of Heihe river basin

**Abstract:** With three periods of remote sense data since 1960s and the long-term observed data of groundwater since1980s, the changes of the groundwater resources in the middle reach of Heihe River Basin in recent three decades are analyzed with the aspects of groundwater recharge and discharge system. The results indicate that the groundwater recharge were reduced by $2.168*10^8 m^3/a$ in the former fifteen years (1969-1985) but increased by $0.134*10^8 m^3/a$ in the later fifteen years (1986-2000) due to the different intensity of land-use and land-cover changes. The groundwater discharge decreased of $2.035*10^8 m^3/a$ due to land-use and land-cover changes during 1969-1986, and it increased of $0.678*10^8 m^3/a$ with the both influences of LUCC and groundwater pumping. Resulting from the changes of groundwater recharge and discharge systems, the groundwater storage decreased $0.133*10^8 m^3/a$ during 1969-1986 and $0.545*10^8 m^3/a$ during 1986-2000. As long as under the reasonable range of exploitation (less than $3.0*10^8 m^3/a$), the land-use changes would control the changes of regional groundwater resources. Influenced by the land-use and land-cover changes and the large-scale exploitation in the recent decade, the groundwater resources present apparent regional differences in Zhangye Basin. Realizing the characteristics of spatial-temporal variations of regional groundwater resources may make the programming and management of water and soil resources more scientific and reasonable.

**Key words:** Groundwater system, Groundwater resources, Change, Cause, Heihe River Basin

## Introduction

Nowadays, the research of the influence of land-use and land-cover changes on the regional water balance is most vigorous in the international hydrological fields, and lots of research indicates that large-scale land-use and land-cover changes are the important factors leading to the regional climate and hydrological cycle changes (Hutjes et al., 1998; Zhang et al., 2001). Therefore, the research plan LUCC established by IGBP and IHDP, one key problem was to understand the influence of the regional land-use and land-cover changes on hydrological process and water resources (Hoff, 2002; Sun et al., 2003; Suzanne, 2001). Lots of research shows that the regional land-use and land-cover changes remarkably affect the regional hydrological cycle process (Deng, et al., 2003; Fu et al., 2001; Zhang et al., 2001), and that the influence of land-use and land-cover changes in the catchment scale on hydrological process, including the groundwater system, are the pop research field and become another important developing field in hydrology.

Groundwater system is the most important portion of whole catchment hydrological process; therefore, every change of hydrological processes must have some impacts on the groundwater system (Schwarts et al., 2003). The characteristics of water resources in arid region determine that groundwater is usually the most important origin and the best water supply choice in such region, at the same time, groundwater is also the primary factor to maintain arid life oasis, especially the social-economic developments in deserts. Worldly, groundwater resources are actually irreplaceable in resolving water scarcity, and scientific evaluation and effective management, which were depended on the recognition to the groundwater changes and its causes, are the important guarantees and necessary preconditions to explore groundwater resources in arid region (Mtembezeka et al., 1997; Alley et al., 1996). In most cases, the land use and land cover changes and human pumping activities are the main factors that lead to the changes of groundwater resources. Thereinto, actual estimation of the influence of human activities on groundwater system is the critical part in establishing reasonable utilization program of regional groundwater resources (Sato, et al., 2003; Asmuth, et al., 2001; Alley et al., 1999). The previous study of the influence of human activities on groundwater system mainly focused on the aspect of the intensity and reasonability of groundwater utilization, but ignored the influence of land-use changes on the groundwater system in the basin. Actually, as the important part of regional hydrological cycle, groundwater system has strong response to land-use and land-cover changes. Selecting Zhangye Basin of Heihe River middle reach in Hexi Corridor as the study area, we analyze the cause of groundwater resource changes, especially the response characteristics of arid groundwater system to land-use changes.

## 1. Study area and methods.

### 1.1 Study area

Taking the Zhangye Basin in the middle reach of Heihe River—the second longest inland river in China as the study area, which is located in the middle sect of Hexi Corridor, between 97° 20′ ~102° 13′ E, 37° 28′ ~39° 59′ N. The total area is $421.4\times10^4 hm^2$. It is the typical continental temperate climate with scarce precipitation and strong evaporation, the mean annual precipitation is 62-280mm and the mean annual evaporation is 1000-2000mm. Since 1951 no obvious changes in surface runoff and atmospheric precipitation were observed in the region, or roughly kept stable (Zhang, et al., 2003). The topography in the region dips from southeast to northwest, with a slope of 25-4‰. Geomorphologially, the southern part is the piedmont alluvial, alluvial-diluvial Gobi plain and the middle part of the basin is alluvial-diluvial fine soil plain. Owing to the limitation of landform, deposits and tectonic conditions groundwater mainly comes from Quaternary interstitial water. From the southern piedmont to the northern basin centre the aquifer consists of single unconfined aquifer transiting to multilayer confined aquifer, and the groundwater table gradually becomes shallow to reach the spring overflow zone (Gao and Li, 1990; Wang and Cheng, 1999). According to landform, aquifer structure and the topographic units, the study area is divided into four hydrogeologic units from south to north: the upper-middle part of alluvial-diluvial fan in the south, the lower part of alluvial-diluvial fan, the fine-grained soil plain in the basin center, and the river valley plain in the lower reach of the basin (Figure 1).

In the past two decades, land-use and land-cover in Heihe River Basin changed intensively, which was indicated by the shrink of the natural oasis system, namely, the expansion of man-made oasis system and the abandonment of original riverway caused by the increase of irrigated fields (Wang and Cheng, 1999; Wang et al., 2002). All these changes would lead to the thorough spatial-temporal variations of water resources system, especially those of such core factors as recharge, runoff and discharge of groundwater system.

## 1.2 Method and data

The elementary formula of composing change and management of groundwater resources is as follows (Sato, et al., 2003):

$$Q_R - Q_D = \Delta S \qquad (1)$$

Where: $Q_R$ is the groundwater recharge, such as riverway infiltration, precipitation infiltration, irrigating water infiltration, and groundwater lateral inflow; $Q_D$ is the groundwater discharge, mainly the spring outflow, evapotranspiration of unconfined groundwater, exploitation and groundwater lateral outflow; $\Delta S$ is the groundwater change of the entire system. Changes of all these composing factors reflect the response of groundwater system to land-use and land-cover changes.

1.2.1 Method for analyzing the changes of recharging and discharging factors

In recharging factors, the precipitation infiltration is ignored in this study because a little of precipitation in the arid inland plain which had little influence on groundwater resources. The analyzing method of the main factors—riverway and irrigating water infiltration is as follows:

For the recharge of riverway water: $\Delta Q_r = \sum_{i=1}^{n} q_i \Delta L_i \lambda_i$ (2)

While for the main stream, the riverway is divided into two parts—the part of head-up above the main irrigation cannel diversion mouth and that of head-down from diversion mouth to spring outflow area. The head-up part infiltration is closely related to the stable mountainous out runoff but changed for power generation diversion with a stable volume per every year, so its measurement is calculated as a constant in this study.

For the recharge of the part of head-down:

$$\Delta Q_{rm} = (Q_0 - Q_{RI} - \Delta q_c)\lambda_m \qquad (3)$$

In the formula (2) and (3), $q_i$ is the mountainous out runoff of each river; $\Delta L_i$

represents length change of each river; $\lambda_i$ is infiltration coefficient; $Q_0, Q_{RI}$ represent the mountainous out runoff of main stream and head-up river seepage, respectively; $\Delta q_c$ is the change of water diversion of head-up river part, which is close to irrigation field; $\lambda_m$ is the riverway infiltration rate of the part of head-down part to spring outflow section.

Irrigating water recharge is farther divided into canal infiltration and field infiltration, and the analyzing formula is shown as follows:

For the recharge of canal: $$\Delta Q_c = q_c(1-\Delta\alpha)\beta \quad (4)$$

For the recharge of field: $$\Delta Q_i = \sum_{j=1}^{m} \Delta F_j q_{0j} \eta_j \quad (5)$$

In which: $q_c, q_0$ represent the water diversion of head-up river and the net irrigation rating, respectively; $\Delta\alpha$ is the change of canal utilizing coefficient along with canal length; $\beta, \eta_i$ represent the canal infiltration coefficient and irrigating infiltration coefficient, respectively; $\Delta F_j$ is the area change of each irrigating field.

In the groundwater discharging factors, there are mainly the groundwater evapotranspiration, spring outflow and the groundwater pumping. The field with different type of land-use and land-cover has different evapotranspiration of groundwater, and the evapotranspiration magnitude was controlled by groundwater level too. Therefore the groundwater evapotranspiration is the coupling result of groundwater level and land-use changes, shown in the following formula:

$$\Delta Q_E = \sum_{p=1}^{K} \sum_{v=1}^{L} F_{p,v} \gamma_{p,v} \quad (6)$$

In which, $F_{p,v}, \gamma_{p,v}$ represent the area of $p$ th divided region according to groundwater level ($hm^2$), and evapotranspiration intensity in $v$ th sub-area according the land using and land cover type, mm/a.

The increase of the area of well irrigating field leads to the increase of exploitation that is closely related to the land-use changes. Additionally, spring outflow, indirectly affected by the land-use changes, is determined by the change of groundwater level. The two factors of groundwater discharge were determined by the statistical data of the changes of exploitation and spring outflow.

1.2.2 Method for analyzing the groundwater storage changes

Based on the hydrogeologic divisions of the entire region and using the observing data of groundwater table changes, the annual variations of groundwater storage are calculated as following formula, which comes from Darcy Law.

$$\Delta W_{ij} = \mu_i F_i(\overline{H_{ij}} - \overline{H_{i0}}) \quad (7)$$

Where: $\Delta W_{ij}$ is the relative groundwater storage change of the $j$th year in the $i$th division area compared to the groundwater storage of the year of 1981 (1984) when it start to observe the groundwater table, $m^3$; $\mu_i$ is storage coefficient, no dimension; $F_i$ is the area of $i$th division, $hm^2$; $\overline{H_{ij}}$, the average observing groundwater level of the $j$th year in the $i$th division area, m; and $\overline{H_{i0}}$ is the average observing groundwater level of the year of 1981 in the $i$th division area, m.

1.2.3 Data sources and parameters

(1) Data of land-use changes: With the regional aerial data of 1969, TM data for regional satellite remote-sense research of 1986 and 2000, we marked the plots of diverse land-use in the topographic map of 1:100000 according to the national standard of the division of land-use (Wang et al., 2002), and picked up the areas of irrigating field, grassland, woodland, desert (naked rock, soil, desert and Gobi, et al), river, and canal system. And then, based on the groundwater table isograms of 1986 and 2000, compared with the land use change data obtained from the satellite remote-sense data, the areas of land use change under the groundwater table less than 1.0m, 1-3.0m, 3-5.0m and 5-10.0m were respectively calculated.

(2) The observing data of groundwater: There are 54 observing points along the Heihe River in Zhangye Basin, in which, the observation of 28 points began in 1980 and the effective data concerning the average annual and mensal observing values of two decades, and the observation of the other 26 points began in late 1983 and the effective data concerning he average annual and mensal observing values of 17 years.

(3) Parameters: In 1986-1989 lots of large-scale investigation of groundwater resources was conducted successively, and through some fields pumping test, fields groundwater dynamic observation, a serial of parameters were established in Zhangye Basin by Gansu Hydrogeological Investigation Team (Gansu Hydrogeological Investigation Team, 1990). The permeability coefficient, hydraulic conductivity, Specific yield, irrigating infiltration coefficient and evapotranspiration intensity used in this paper come from these broadly used testing results (Gansu Hydrogeological Investigation Team, 1990; 1998) .

Table 1 The measurement of parameters used in this study

| Groundwater table (m) | | <1 | 1-3 | 3-5 | 5-10 | Subarea | Upper-middle part of alluvial-diluvial fan | Fine-grained soil plain |
|---|---|---|---|---|---|---|---|---|
| Irrigating infiltration coefficient (%) | | 28.1 | 34.9 | 28.4 | 18.5 | Specific yield (m3/m) | 0.15 | 0.1 |
| Evapotranspiration of unconfined groundwater (mm/a) | Irrigating area | 327.79 | 55.3 | 41.0 | 12.0 | Riverway infiltration rate (%) | 0.32-14.7 | 0.67-1.52 |
| | grassland | 191.43 | 34.69 | 23.9 | 7.01 | Canal leak recharging rate (%) | 0.7-0.8 | 0.8-0.9 |

## 2. The changes of the groundwater recharging system

### 2.1 The changes of infiltration recharge of riverway and channel

Before 1985, $5.186*10^8 m^3/a$ runoff of the distributaries of Heihe River out of the mountainous in Zhangye Basin was taken into canals and reservoirs, which caused the intensive changes of riverway distribution (Table 2). Based on such information, the riverway infiltration recharge decreased $1.608*10^8 m^3/a$ in 1970-1985 and $0.266*10^8 m^3/a$ in 1986-2000. Moreover, infiltration recharge decreased by $0.529*10^8 m^3/a$ in the head-up part of riverway due to the power generation diversion $7.2*10^8 m^3/a$ from the main river at the mountain out mouth before 1985. After the water diversion to canals, infiltration decreased $1.156*10^8 m^3/a$ in the head-down riverway part between canal diversion mouth and spring outflow zone in 1970-1985 and $0.313*10^8 m^3/a$ in 1986-2000 (Table 2).

Table 2 The changes of infiltration recharge of riverway and channel

| Period of time | Changes of river length (km) | Changes of diversion ($10^8m^3/a$) | Changes of river infiltration ($10^8m^3/a$) | Changes of canal diversion ($10^8m^3/a$) | Canal utilizing rate | Changes of canal infiltration | Changes of canal system |
|---|---|---|---|---|---|---|---|
| 1970-1985 | -59.07 | 6.02 | - 3.293 | 2.27 | 0.5 | 0.908 | - 2.385 |
| 1986-2000 | -17.63 | 1.49 | -0.579 | 1.92 | 0.65 | 0.537 | -0.042 |

During 1970-1985 the irrigating agriculture developed with a most fast rate in the Zhangye basin, and the length of canal system and its water efficiency increased, respectively, which directly lead to more canal water diversion. Additionally, the average canal efficiency was 0.5 before 1985, but after 1986, especially in 1990s, it increased to 0.65 averagely. Based on such information and the former formula, the changes of canal infiltration recharge are calculated and listed in table 2. In the fifteen years before 1985, with the increase of water diversion the canal recharge to groundwater increased $0.908*10^8m^3/a$ and $0.537*10^8m^3/a$ in 1986-2000. The changes of river infiltration concentrated on the upper-middle part of alluvial-diluvial fan because a large amount of rivers were inducted into canals or reservoirs, while the changes of canal infiltration concentrated on the center of man-made oasis located in the middle-lower part of alluvial-diluvial fan and fine-grained soil plain.

**2.2** The changes of infiltration recharge of irrigating field areas

Groundwater recharging changes caused by the changes of irrigating field areas are the one of the most important factors of groundwater recharge system changes. In the arid inland region, the groundwater table of the area where irrigating infiltration could recharge to groundwater is generally lower than 10m. To compare the the groundwater table isograms of 1986 and 2000 with the land-use change plots in 1969-1986 and 1986-2000, the two periods irrigating area changes with different groundwater table were calculated and listed in table 3. Different field has different irrigating quota, for example, the average total irrigating quota in Zhangye is $7872\sim14191.5m^3/hm^2$, but it is$10092\sim10957.5$ $m^3/hm^2$ in Linzhe and $9618\sim17356.5$ $m^3/hm^2$ in Gaotai. The efficiency of irrigation system was selected the average 50% before 1985 and 65% after 1986. Then it is calculated that the increase of recharge owing to the increase of irrigating area is $2169.69*10^4m^3/a$ in 1970-1985, and $1767.09*10^4m^3/a$ in 1986-2000 (Table 3).

Table 3 Influence of the changes of irrigating fields on groundwater recharge

| Groundwater table (m) | | <1 | 1-3 | 3-5 | 5-10 | Total |
|---|---|---|---|---|---|---|
| 1970 ~ 1985 | Area changes of irrigating fields ($km^2$) | 5.5 | 41.35 | 40.67 | 53.05 | 140. 57 |
| | Average irrigating rate ($m^3$/ha) | 4950 | 5400 | 6150 | 6150 | |
| | Infiltration ($10^4m^3$) | 76.5 | 779.28 | 710.34 | 603.57 | 2169. 69 |
| 1986 ~ 2000 | Area changes of irrigating fields ($km^2$) | 6.5 | 15.41 | 30.03 | 46.34 | 98. 28 |
| | Average irrigating rate ($m^3$/ha) | 5250 | 7035 | 7560 | 7560 | |
| | Infiltration ($10^4m^3$) | 95.89 | 378.34 | 644.75 | 648.11 | 1767. 09 |

## 3. The changes of the groundwater discharge system

Since evapotranspiration mainly happened in the zone whose groundwater table is less than 10m (Gansu Hydrogeological Investigation Team, 1990), where the most grassland with low cover degree (such as the desert grassland), semi-fixed and fixed dune, and the desert have turned to irrigating fields, the changes of irrigating area from the original grassland according to the groundwater table were used to calculate the influence of land-use changes on evapotranspiration. The groundwater evapotranspiration in the grassland with high cover degree (>70%) in the plain is thought to be equal to that of cropland (Gansu Hydrogeological Investigation Team, 1998). The influence of woodland on groundwater evapotranspiration is intensive. According to some research in this region (Gansu Hydrogeological Investigation Team, 1998), the evapotranspiration of woodland is about 2700$m^3$/ha. All the groundwater evapotranspiration changes were calculate with the former formula and shown in table 4.

Table 4 Evapotranspiration changes in different land-use

| Groundwater table (m) | | <1 | 1-3 | 3-5 | 5-10 | Woodland changes | Total |
|---|---|---|---|---|---|---|---|
| 1970 ~ 1985 | Area changes of irrigating fields ($km^2$) | 2.3 | 31.15 | 38.54 | 53.05 | 88.45 | 213.49 |
| | Vaporizing intensity ($m^3$/ha) | 3277.9 | 553 | 410 | 120 | 2700 | |
| | Evaporation of unconfined groundwater ($10^4m^3$) | 75.39 | 172.25 | 158.02 | 63.66 | 2388.15 | 2857.47 |
| 1986 ~ 2000 | Area changes of irrigating fields ($km^2$) | 3.5 | 12.74 | 30.03 | 46.34 | -33.03 | 48.58 |
| | Vaporizing intensity ($m^3$/ha) | 3277.9 | 553 | 410 | 120 | 2700 | |
| | Evaporation of unconfined groundwater ($10^4m^3$) | 114.72 | 70.45 | 123.12 | 55.6 | -891.81 | -527.92 |

The other groundwater discharging items are spring outflow and human exploitation, which are calculated directly used the statistical and metrical data according to the investigating results obtained by Gansu Hydrogeological Investigation Team (Gansu Hydrogeological Investigation Team, 1990; 1998). The measurement of the changes of spring outflow and groundwater exploitation is shown in table 5, in which the spring outflow of 2000 is the prognosticated result with some statistic model (Gansu Hydrogeological Investigation Team, 1998).

Table 5 changes of spring outflow and exploitation

| Year | 1970 | 1985 | 1995 | 2000 | 1970-1985 | 1986-2000 |
|---|---|---|---|---|---|---|
| Spring outflow ($10^8m^3/a$) | 10.19 | 7.23 | 5.34 | 5.17 | -2.96 | -2.06 |
| Exploitation ($10^8m^3/a$) | 0.186 | 0.83 | 1.086 | 3.62 | 0.644 | 2.79 |

According to the results of table 4 and table 5, the change of groundwater discharging system cause by land-use changes in Zhangye Basin averagely decreased $2.035*10^8m^3/a$ in the fifteen years before 1985 mainly because spring outflow decrease sharply, while in the fifteen years after 1986 it increased $0.6785*10^8m^3/a$ mainly because outflow tended to decrease more slowly and the exploitation increased intensively.

## 4. Groundwater storage changes and balance analysis

### 4.1 Groundwater storage changes

The groundwater storage changes are calculated with the formula (7) and the observing data of groundwater level variations in every hydrogeologic unit, and the results are shown in table 6. The results indicate that the groundwater storage of upper-middle part of alluvial-diluvial fan presents an apparent declining trend, thereinto, the storage declined 6.27 $\times 10^6m^3$ annually in the 1980s, and $15.08\times 10^6m^3$ in the 1990s, totally $220.7\times 10^6m^3$ in two decades, and averagely $11.0\times 10^6m^3$ every year. In the lower part of alluvial-diluvial fan, groundwater storage tended to decline generally, but there's spatial-temporal distribution. In the 1980s storage declined slowly, thereinto, it decreased $11.80\times 10^6m^3$ totally in 1980-1989, that was, $1.2\times 10^6m^3$ every year. And in 1981-1983 storage did not decline but increase. In the 1990s, however, storage in this area declined rapidly, totally $56.86\times 10^6m^3$ in the decade, and averagely $5.7\times10^6m^3$ every year. In the fine-grained soil plain, groundwater variation kept relatively stable, and the change was between $0.02\times10^6m^3\sim0.33\times10^6m^3$. In the river valley plain, the range of storage variations was small, and from the late 1980s and the early 1990s, storage showed an increasing trend.

Table 6 annual changes of regional groundwater level and storage

| Subarea \ Year | 1981 (1984)—1985 | | 1986—1990 | | 1991—1995 | | 1996—2000 (2001) | |
|---|---|---|---|---|---|---|---|---|
| | Level change (m) | Storage change ($10^6m^3$) | Level change (m) | Storage change ($10^6m^3$) | Level change (m) | Storage change ($10^6m^3$) | Level change (m) | Storage change ($10^6m^3$) |
| Upper-middle part of alluvial-diluvial fan | -0. 60 | -15. 82 | -1. 11 | -29. 39 | -1. 96 | -52. 04 | -2. 47 | -65. 60 |
| Lower part of alluvial-diluvial fan | -0. 32 | -3. 42 | -1. 06 | -11. 21 | -1. 89 | -19. 97 | -2. 43 | -25. 68 |
| Fine-grained soil plain | 0. 03 | 0. 11 | -0. 05 | -0. 17 | -0. 04 | -0. 15 | -0. 18 | -0. 66 |
| River valley | -0. 03 | -0. 40 | -0. 22 | -2. 95 | 0. 49 | 6. 77 | 0. 7 | 0. 93 |
| Zhangye Basin | ~ | -19. 53 | ~ | -43. 72 | ~ | -65. 39 | ~ | -91. 01 |

### 4.2 Balance analysis of recharge and discharge of groundwater system

Changes of regional groundwater recharging system: $\Delta Q_R = \Delta Q_r + \Delta Q_{rm} + \Delta Q_c + \Delta Q_i$, based on this formula and the former results, the changes of recharge of diverse time period in Zhangye Basin are analyzed as following:

1970-1985: $\Delta Q_R$=−2.385+0.217= −2.168 ($10^8$ $m^3/a$);

1986-2000: $\Delta Q_R$=−0.042+0.176= 0.134 ($10^8$ $m^3/a$).

Changes of regional groundwater discharging system: $\Delta Q_D = \Delta Q_E + \Delta Q_M + \Delta Q_S$, where $\Delta Q_M, \Delta Q_S$ represent the changes of groundwater exploitation and those of spring outflow, respectively.

1970-1985: $\Delta Q_D$= −2.035 ($10^8$ $m^3/a$); 1986-2000: $\Delta Q_D$=0.6785 ($10^8$ $m^3/a$).

The result: 1970-1985: $\Delta Q_R - \Delta Q_D$= −0.133 ($10^8$ $m^3/a$);

1986-2000: $\Delta Q_R - \Delta Q_D$=−0.545 ($10^8$ $m^3/a$).

The result indicates that the changes of groundwater recharging and discharging system made groundwater storage decline $0.133*10^8m^3/a$ before 1985, and $0.545*10^8m^3/a$ in1986-2000. While for groundwater storage change calculated with the change of groundwater level (shown in table 6), it declined $0.195*10^8m^3/a$ in 1981-1985 and $0.667*10^8m^3/a$ in 1986-2000. Comparing the results of two calculating method, we get that the deviation of the results before 1985 is $0.062*10^8m^3/a$ and $0.126*10^8m^3/a$ in 1986-2000, and their relative errors are both less than 20%, while it is unable to analyze the errors for the results of 1970-1986 because the storage change calculated with the change of groundwater level was only between 1981-1985. However, the two storage change results before 1985 have a similar trend. Considering that all parameters used in this study are the testing results carried out by Gansu Hydrogeological Investigation Team in 1980s, which unavoidably have some deviation for the hydro-geological condition changes, and the investigating data of spring outflow after 1990 are absent and remedied by using some statistics model, which also lead to the errors, therefore, the analysis results have good veracity under such study precision.

Presuming that the increase of exploitation is taken into rational extent (such as to $2.62*10^8m^3/a$ in 2000), the balanced relationship between recharge and discharge in 1986-2000 should be: $\Delta Q_R - \Delta Q_D = 0.457*10^8m^3/a$, followed by a little increase of regional groundwater storage. The results showed that, as long as we keep a reasonable range of exploitation (less than $2.62*10^8m^3/a$ in the study area), land-use changes would control the changes of groundwater resources. In the recent fifteen years, large amount of exploitation concentrated on the middle-lower part of alluvial-diluvial fan, but the changes of recharging system caused by the land-use changes primarily happened in fine-grained soil plain in the basin center and the river valley plain in west of the basin, so the apparent diversity of regional changes of groundwater resources appeared in the entire region. Groundwater storage in the upper-middle and lower part of alluvial-diluvial fan decreased continuously, but in the fine-grained soil plain and river valley plain it increased apparently, instead (Table 6).

## 5. Conclusion and discussion

Since the large-scale development in Zhangye Basin of Heihe River Basin from the 1970s, groundwater recharge decreased $2.168*10^8m^3/a$ due to the land-use changes up to

1985, and discharge decreased $2.035*10^8m^3/a$. All these changes led to $0.133*10^8m^3/a$ decrease of groundwater storage. In the later fifteen years (1986-2000), regional land-use had further changes and human pumping expanded too, which led to $0.1342*10^8m^3/a$ net increase of recharge, and led to $0.6785*10^8m^3/a$ net increase of discharge. All these changes made groundwater storage decreased $0.545*10^8m^3/a$. However, under reasonable exploitation, land-use changes would control the changes of regional groundwater resources.

In recent three decades, the former fifteen-year (1970-1985) is a period when regional land-use changed intensively, and the impact on groundwater recharging system occupied 92.27% of that of thirty years. Thereinto, riverway and canal system changes had the biggest impact on the groundwater recharge, which occupied 91.6% of the total change of recharging system. The residual 8.4% came from the changes of irrigating areas. In all the discharging factors, spring outflow changed most, and of evapotranspiration, which was directly related to land-use was 7.33% of the total discharge. In the later fifteen-year period (1986-2000), the range of land-use changes was relatively smaller than former fifteen years, followed by smaller influence on groundwater. In contrast to that in the former fifteen-year period, the impact of change of irrigating area occupied 80.7% of total recharge. From 1986 on, groundwater exploitation increases and apparently affected the groundwater discharging system. Under the combined influence of land-use and exploitation changes of groundwater resources in the basin presented apparent regional diversity in the later fifteen years.

It is well known that influence of land-use and land-cover changes on water resources system is intensive in arid inland river basin, and that the spatial-temporal distribution of surface water system changes continuously with the changes of land-use pattern. This study indicates that land-use and land-cover changes also affect intensively the groundwater system in the basin, and in some extent, the land use change would control the groundwater changes. In Zhangye basin, the land use change and human pumping are the two key factors that control the groundwater resources change. Realizing the impact of land-use changes on groundwater system may make the programming and management of water and soil resources more scientific and reasonable.

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# Role of glacier runoff in the Heihe Basin

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**Abstract**

We estimated the fluctuation of precipitation and air temperature from Dunde ice core data since 1606 comparing to meteorological data taken near the July 1st glacier since 1930s. Then, we calculated the discharges from glaciers and glacier-free area.

Furthermore, we analyzed the sensitivity of those discharges to meteorological factor. The result revealed that calculated discharge from glacier-free area increased with precipitation. Meanwhile, calculated discharge from glaciers decreased with precipitation. Since little precipitation cause expose the glacier ice surface, which can absorb almost solar radiation, then glacier melt accelerated. Then, relatively large discharge from glacier can be provided when the discharge from glacier-free area is less. Therefore, discharge from glacier make up for the shortage of discharge from glacier-free area due to less precipitation. Then, water supply for living people in the oasis and desert would have been maintained from ancient days.

**Introduction**

There are several vast arid region in the north west of China. There is relatively high precipitation (more than 300 mm $yr^{-1}$) at high elevations in mountain areas. On the other hand, there is little precipitation (less than 50 mm $yr^{-1}$) downstream along the river. From olden days, melt water of glaciers and snow on those mountains have provided

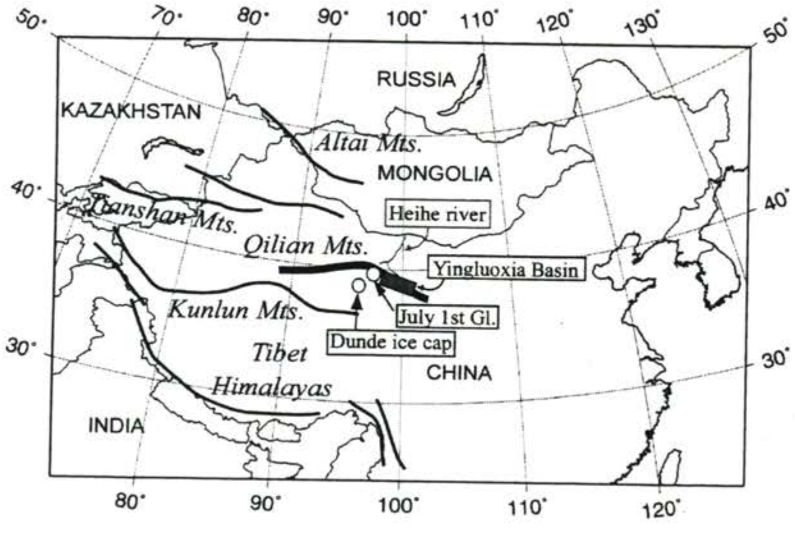


Figure 1. Location map of Heihe River and Yingluoxia Basin.

drinking water and water for irrigation to the people living in those oasis cities. Purpose of this study, therefore, is to estimate the discharge from glaciers using the ice core data and elucidate the characteristic of the discharge.

## Location

Heihe river basin comprises Qilian mountains in the southern part, oasis cities in the middle part and vast Gobi Desert in the northern part. Qilian mountains locates on the northern fringe of the Tibetan plateau, Northwest China (Fig. 1), and there are relatively a lot of precipitation. There have been a lot of irrigated area in the Oasis cities, and nomad people have been living in the desert area from ancient days. Yingluoxia basin locates at the mountain portion of the Heihe river basin (Fig. 1), and we can assume that the discharge from this basin has not been influenced by human activity. Yingluoxia basin was 10009 km$^2$ in area and there area 73 km$^2$ of glacier area in this basin (Gao and Yang, 1985). Glacier area, therefore, attain 0.7 % of the whole Yingluoxia basin.

## Data set for calculation

*Reconstruction of historical air temperature*

Air temperature and precipitation was estimated from ice core taken at Dunde ice cap (Thompson *et al.*, 1998). Dunde ice cap locates at 100 km south-west from July 1st Glacier in Qilian mountains (38°06'N, 96°24'E). In this region, stable isotope of precipitation is high when air temperature is high, and variation of stable isotope of precipitation reflect variation of air temperature (Tian et al., 2003; Araguas-Araguas *et al.*, 1998; Johnson and Ingram, 2004), and there are relatively large precipitation during summer season (from June to August) (Ding and Kang, 1985). We, therefore, compared the summer (JJA) temperature and isotope of ice core data. Figure 2 shows the 12 years running mean of variation of stable

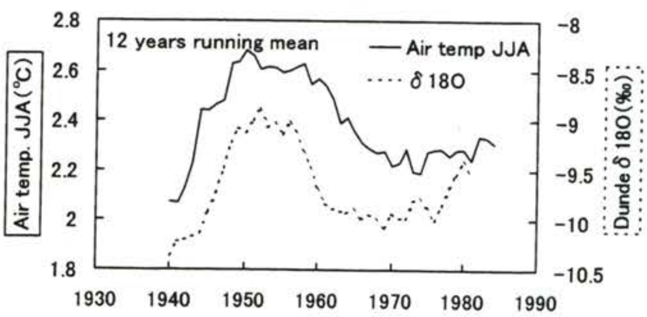


Figure 2. 12 years running mean of summer (JJA) air temperature and isotope of Dunde ice core.

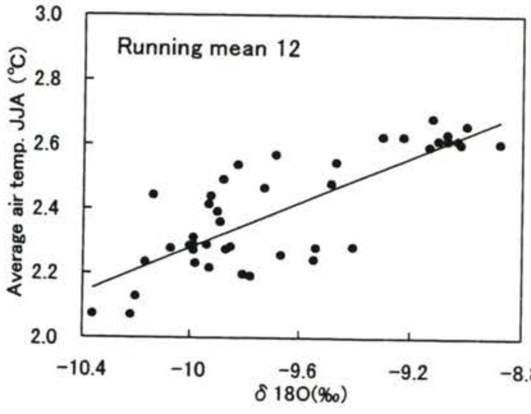


Figure 3. Relation between 12 years running means of JJA temperature at Jiuquan and stable isotope in the Dunde ice core.

isotope fluctuation in the Dunde ice core and temperature at Jiuquan 90 km north east from July 1st Glacier. And we can estimate JJA air temperature from the relation in Fig. 3. Then, annual air temperature was estimated from JJA air temperature since mean difference between annual air temperature and air temperature averaged during summer (JJA) was 9.3 °C since 1935.

*Reconstruction of historical precipitation*

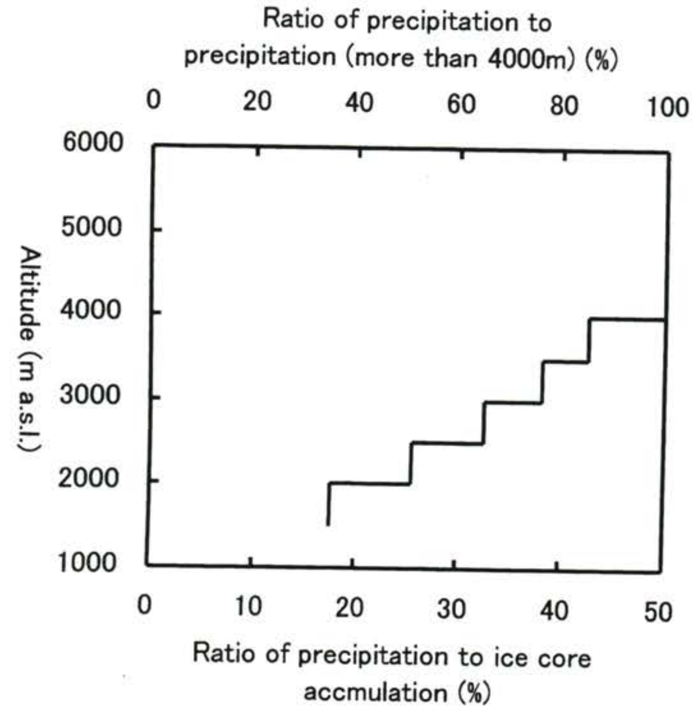


Figure 4. Altitudinal distribution of precipitation in the Heihe Basin.

Observed precipitation at several altitude in Heihe river basin were summarized by Ding and Kang (1985). Figure 4 shows the altitudinal distribution of precipitation ratio assuming precipitation at more than 4000m altitude was 100 %.

Precipitation in the Yingluoxia basin was assumed to be equal fluctuation with Dunde ice core.

Precipitation using calculation for discharge was adjusted so as to the fluctuation of ice thickness would have peaks, in other words, not to simple increase or decrease since terminus of the glaciers in Qilian mountains has repeated to advance and retreat since 1600s (王, 1991).

Figure 5 shows annual air temperature and precipitation data since 1606 reconstructed from ice core data.

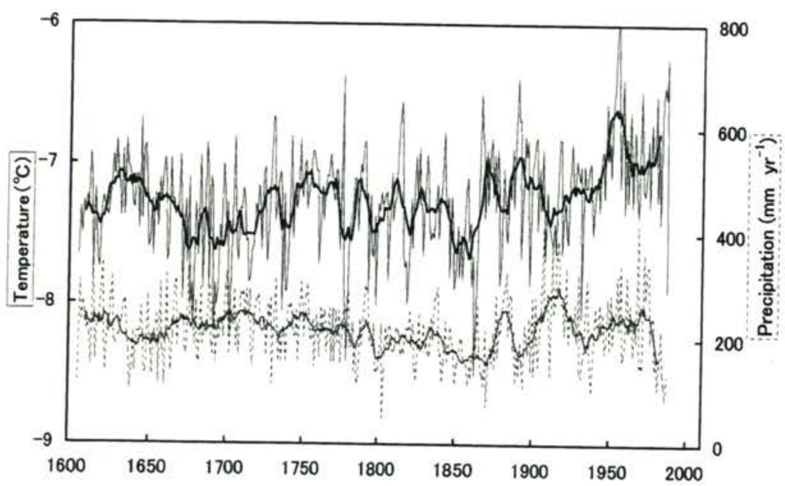


Figure 5. Reconstructed air temperature at 4300 m and precipitation at more than 4000 m altitude from the ice core.

*Assumption of estimating daily data from annual data*

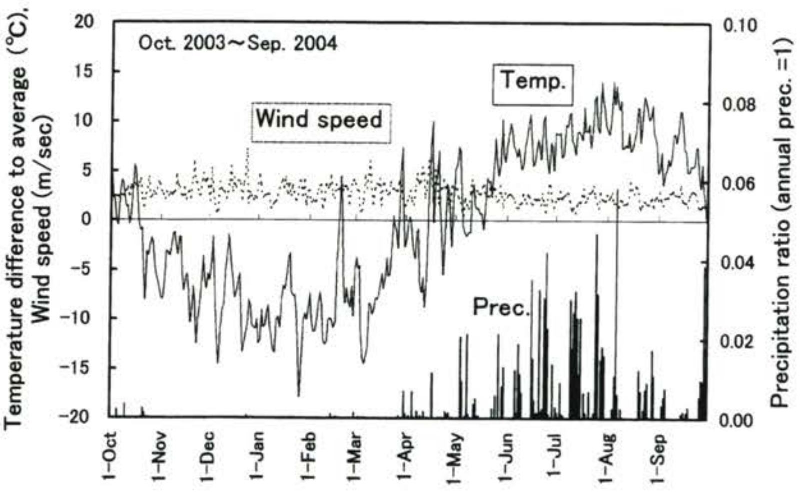


Figure 6
Fluctuation of daily air temperature assuming that the annual air temperature was zero. Precipitation ratio shows the ratio of the daily precipitation to annual precipitation (=1). Wind speed

Daily precipitation and temperature have estimated from annual data estimated from ice core. There was a observed temperature and precipitation data set at the July 1st glacier at the altitude of 4295 m a.s.l. from October, 2003 to September, 2004. We calculated the daily temperature difference from annual average of temperature, and daily precipitation ratio to annual precipitation as shown in the Fig. 6. Then daily temperature and precipitation were calculated by assuming that the daily variation of the temperature and precipitation (as shown in the Fig. 5) were unchanged.

## Calculation

*Discharge calculation at glacier area*

Discharge from glacier area can be calculated as follows,

$$Q_g = P_r + M - R$$

where, $Q_g$ = discharge from glacier area

$P_r$ = liquid precipitation (rain),

$M$ = glacier melt

$R$ = Refreezing of rain or meltwater.

Precipitation can be divided depending on the air temperature. Here, 100 %, 0 % of provability of solid precipitation (snow) occurrences were 0 C° and 6 C°, respectively.

Degree-day factor has been put into common use to estimate melt rate of glaciers in the world (Braithwate, 1995; Johannesson et al., 1995; Hock, 2003; Singh et al., 2000 and so on) But, the method was assumed that the ice or snow melt rate is proportional to only air temperature. Although, the actual melt rate of glaciers depend on not only air temperature, but also solar radiation, albedo, wind speed, humidity and so on. Degree-day factor, therefore, have wide-ranging value depending on the ratio of heat balance elements to total incoming heat as shown in the previous studies (Braithwate, 1995; Johannesson et al., 1995; Hock, 2003; Singh et al., 2000; Kayastha, 2003). Then, it would vary with climate change during past few thousands or hundreds of years, and estimating melt rate with constant degree-day factor would us lead to misunderstand the essence of past environment of glaciers.

But, heat balance methods requires many kinds of meteorological elements, which we can not get from proxy data, such as ice core data, tree-ring data and lake sediment core. There are only air temperature and precipitation, which we can get from those proxy data. Then, we estimated solar radiation and humidity, which was difficult to estimate from proxy records, from precipitation or air temperature, which can be relatively easy to get.

Downward shortwave radiation (:$SR_d$) can be defined by transmissivity (: $\tau$) and shortwave radiation at the top of the atmosphere (:$SR_{top}$) ,

$$SR_d = \tau \, SR_{top}$$

We found the following relation between monthly downward shortwave radiation and monthly precipitation observed at July 1st Glacier at the altitude of 4295 m a.s.l.(Fig. 7). Since precipitation generally increases with cloud amount, which cover over the sun and reduces the ratio of the downward shortwave radiation to shortwave radiation at the top of the atmosphere, in other words, transmissivity.

Figure 8 shows the relation between precipitation and relative humidity. The relation indicates that the precipitation increase with relative humidity.

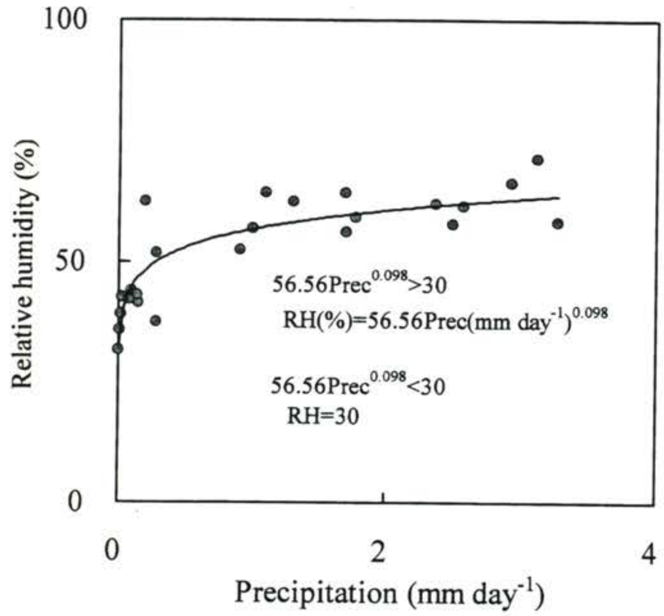


Figure 8.
Relation between monthly average transmissivity (Downward solar radiation/solar radiation at the top of the atmosphere) and daily precipitation in monthly average.

Then, we can estimate relative humidity and downward shortwave radiation from precipitation. Calculation of surface heat balance of glaciers was referred from Fujita and Ageta (2000), which takes into account the ice temperature change and refreezing ice.

*Discharge calculation at Glacier-free area*

It was assumed that there was no change of annual ground water. Therefore, we can calculated the annual discharge from the glacier free-area as follows,

$$Q_f = P - E_f$$

Evaporation at glacier-free area can be calculated from Kang *et al.*(1999) which equation was applied to calculate the evaporation at Urumqi River basin.

For further study, we will estimate evaporation from heat balance method as using in the glacier melt calculation.

**Result**

Figure 9 shows the fluctuation of cumulative mass balance in other words, ice thickness averaged in whole glacier area at July 1st Glacier. Those are calculated from air temperature and precipitation data from the Dunde ice core and NCDC data at Jiuquan. Precipitation was adjusted so as to the fluctuation of ice thickness would have peaks, in other words, not to simple increase or decrease since terminus of the glaciers in Qilian mountains has repeated to advance and retreat since 1600s (王, 1991).

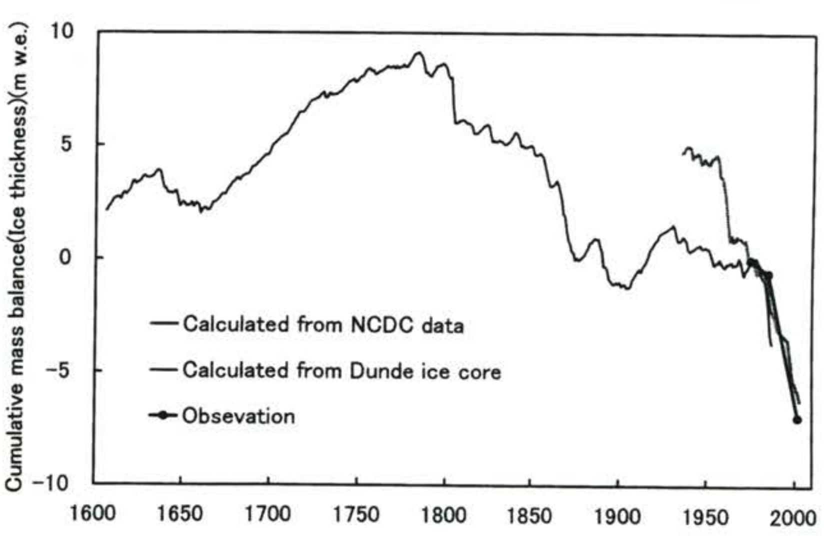


Figure 9. Fluctuation of cumulative mass balance in other words, ice thickness averaged in whole glacier area at the July 1st Glacier.

Figure 10 shows calculated annual discharge and evaporation at the glacier-free area in Yingluoxia Basin since 1606. The total value of the annual runoff and evaporation of each year represents the annual precipitation at the glacier-free area. This figure indicates that the magnitude of fluctuation in precipitation was relatively larger than that of evaporation, and annual discharge depends on mainly precipitation.

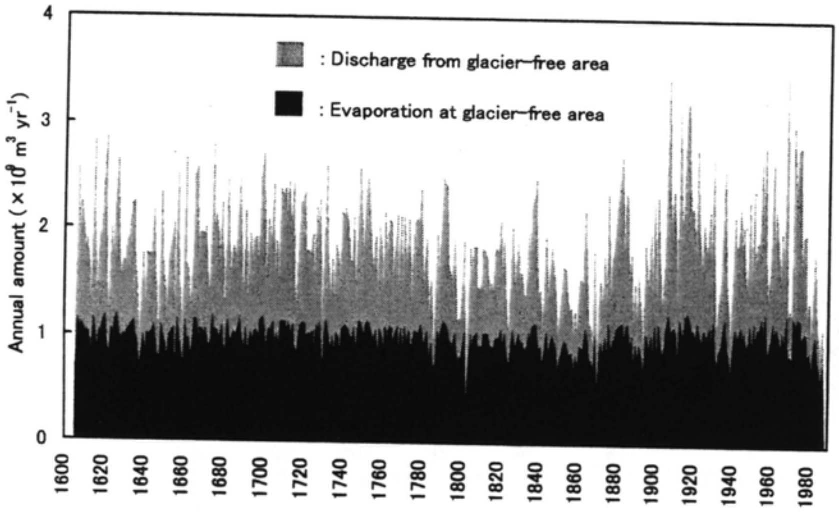


Figure 10.
Calculated discharge and evaporation at the glacier-free area.

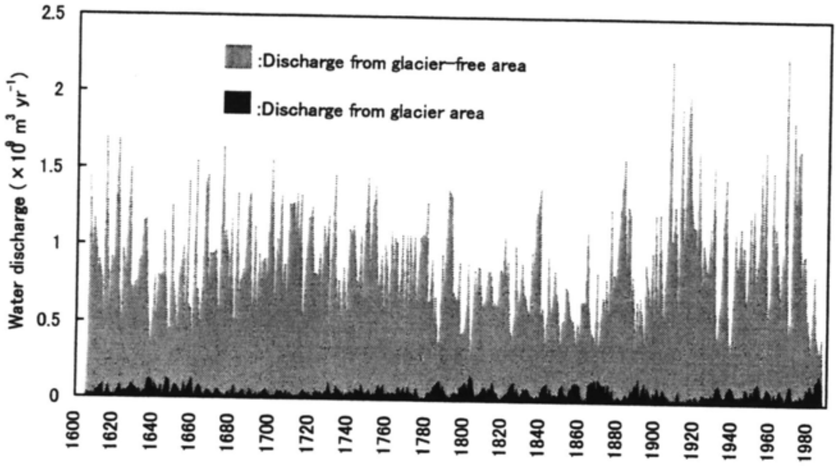


Figure 11.
Calculated discharge from glacier and glacier-free area.

Figure 11 shows the variation of annual water discharge from glacier and glacier-free area since 1606. Average discharge from glacier attain about 10 % of total discharge from this basin since 1606. Observed discharge at Yingluoxia basin was 1.3 - 2.1×10$^9$ m$^3$ yr$^{-1}$ from 1993 to 1999. Calculated discharge was relatively small. Because the precipitation was adjusted to that in the west side of the basin, where precipitation was rather small than the east side.

## Discussion

Sensitivity of the discharge from glacier and glacier-free area to meteorological condition has analyzed to elucidate the characteristic of discharge in mountain area.

Figure 12 shows the relation between discharge from glacier-free area and air temperature and precipitation. It is very clear that the discharge from glacier-free area depend on precipitation.

Figure 13 shows the relation between discharge from glacier area and air temperature and precipitation. Discharge from glacier increase with air temperature, and decrease with precipitation. Little precipitation cause expose the glacier ice surface, which can absorb almost solar radiation, then glacier melt accelerated. Meanwhile, snow tends to cover the glacier surface when there is much precipitation, and snow, which has high albedo, reflect almost solar radiation and glacier was prevented to melt.

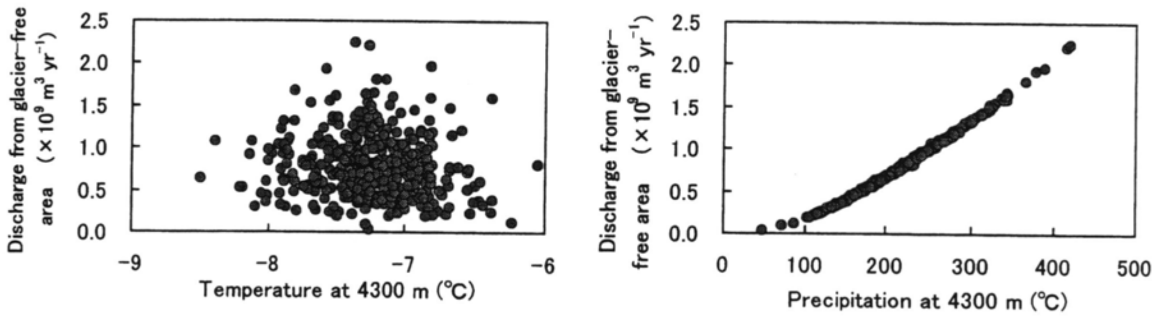


Figure 12. Relation between discharge from glacier-free area and air temperature (left) and precipitation (right).

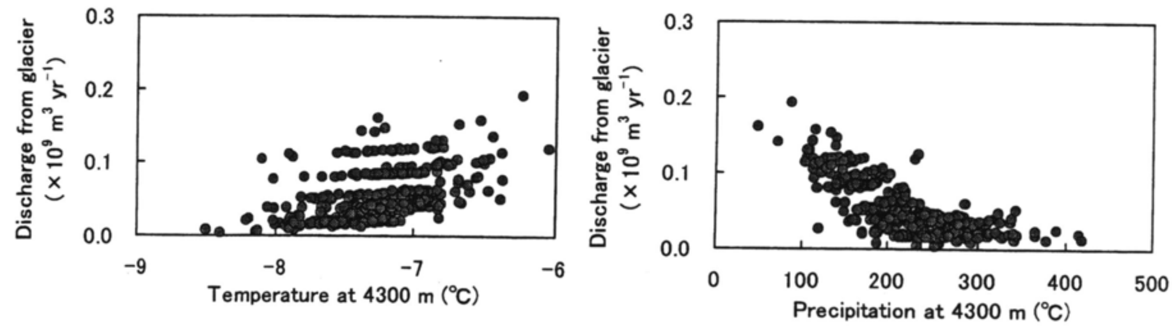


Figure 13. Relation between discharge from glacier area and air temperature (left) and precipitation (right).

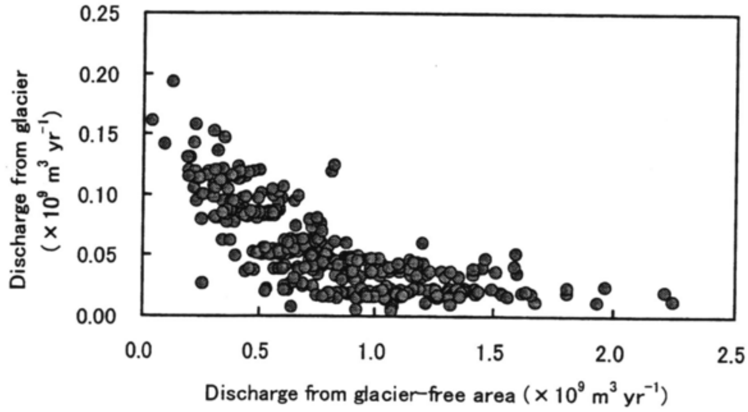


Figure 14.
Relation between discharge from glacier-free area and from glacier area.

Figure 14 shows the relation between discharge from glacier and glacier-free area. The relation can obtained since each sensitivity of discharges to precipitation has in opposite sense. Discharge from glaciers compensate the shortage of discharge from glacier-free area, and play a role of water discharge regulator for stable runoff.

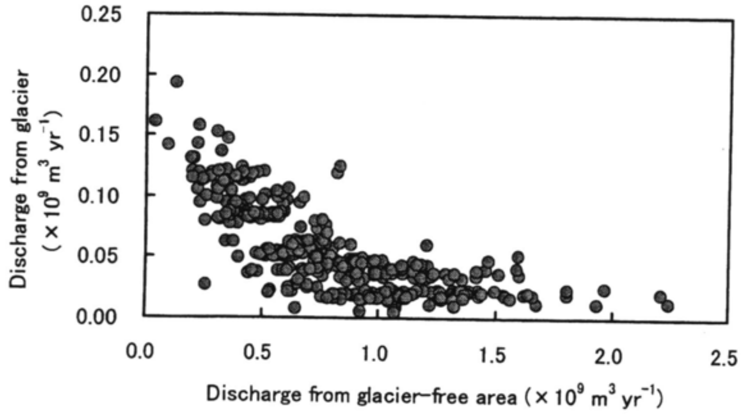


Figure 14.
Relation between discharge from glacier-free area and from glacier area.

## Conclusion

Discharges from glacier and glacier-free area has calculated using air temperature and precipitation estimated from ice core data from 1606 to 1987. Sensitivity of calculated discharge from glacier and glacier-free area has revealed that the discharge from glacier area increase when the discharge from glacier-free area decrease.

We can conclude that the discharge from glacier area has been made up for the shortage of discharge from glacier-free area and has supplied stable waters for drinking and irrigation to the people living in the oasis cities and desert area from ancient days.

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# Research on Current Situation and Change of Agricultural Water Management in the Middle Reaches of Heihe River Basin

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**Abstract:** Taking Zhangye City in the middle reaches of the Heihe River Basin as a case study, the current situation and the background of water resources management system in this region are investigated. The current situation of agriculture water used is analyzed, and the agricultural water assignment, the irrigation management system and the organization are clear about. Then, the measures and the effects for construction of the water-saving society are analyzed, the changes in agricultural water management and agriculture industrial structure are discussed, and the question about sustainable development of the water-saving society is put forward. Finally, through the qualitative analysis on the influence of agricultural water used to the water resources of Heihe River Basin, the recent policy and the new trend of agricultural water used is appraised preliminarily.

## 1 Introduction

### 1.1 Background

In the Heihe River Basin, the problems about the drought, the water shortage and the degradation of the ecological environment are markedly deteriorated. The drastic population growth and the economic development in the past 20 decades cause that the conflict between domestic water resources supply and demand is prominent and that the environment of the downstream region grow worse. The East Juyanhai and the West Juyanhai are dried up, Ejina Oasis is disappearing, and hazards of sandstorm are getting worse.

Therefore, the State Council of the People's Republic of China approved *Heihe River Water Allocation Scheme* in 1997. The Ministry of Water Resources of China carried *General Plan of the Heihe River Basin* into execution in 2001. These ensured the discharge of river water to the downstream area. Zhangye city is constructing into a water-saving society as a model. These measures are very important to the sustainable utilization of water resources and irrigated farming in the Heihe River Basin.

Under such background, through investigating the current situation of agriculture development and the land utilization, and the internal structure and mechanism of the irrigation farming, the research on the influences of the agricultural development and irrigation to the rule of water cycle in the Heihe River Basin become an important topic to solve the water cycle question. Based on investigating the series of measures and these effects, e.g. the discharge of river water to the downstream area and the construction of a water-saving society, and the influences of the agricultural irrigation on the middle reaches, the exploration of the sustainable pattern of agriculture management development adapting the water resources carrying capacity of the Heihe River Basin is meaningful.

### 1.2 Introduction of the region investigated

#### 1.2.1 The Heihe River Basin

The Heihe River Basin is the second largest inland river basin in the arid area of Northwest China.

Its main stream, with a length of 821km, originates in the Qilian Mountains. The upper, middle and lower reaches are respectively the forming, using and vanishing areas of the runoff. The annual volumes of runoff change little, but those in a year change sharply and the transformation between the surface water and the ground water is frequent. The annual precipitation of the upper reaches is 300 mm. The annual precipitation of the middle reaches is 140 mm. This area is rich in sunlight and heat resources, and thus, it has been an important agriculture zone since ancient times. The lower reach is mainly Gobi and desert, where the annual precipitation is only 47 mm.

#### 1.2.2 Zhangye City

Zhangye city is located the middle reaches of Heihe River. The annual precipitation of this region is 98-350 mm and the annual evaporation is 2000-2700mm. Altogether 26 rivers including Heihe River originated in the Qilian Mountains can be developed and utilized. The surface water resources amount is 2.48 billion $m^3$, including Yingluo Gorge Station ($1.58\times10^9 m^3$), Liyuanhe Station ($2.4\times10^8 m^3$), and other stations ($6.6\times10^8 m^3$). The ground water resources amount is $1.8\times10^8 m^3$, and the total water resources amount is 2.65 billion $m^3$. The mean per capita volume of water resources, $1250m^3$, is only 54.2 percent of China and closing to the lower limit of water shortage. So it is a drought region in which no irrigation and no agriculture (Fig.1).

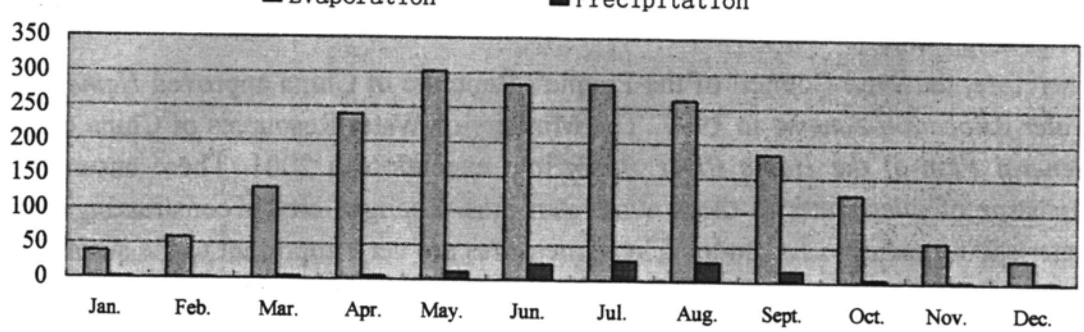


**Fig.1 Average monthly evaporation and precipitation of Ganzhou Region (mm)**

The city of Zhangye is the traditional irrigation region, the most developed area of agricultural economy in Gansu Province, and the national important production base of grain, rape, fruit and vegetables. And it is the famous base of transporting the vegetables from the West to the East and also has 80 kinds Chinese traditional medicine. The city is an oasis on the middle reaches of the Heihe River, where the cultivated land, the population, the water consumption, and the GDP occupy 95%, 91%, 83% and 89% of the total amounts of the basin respectively.

Heihe River is main water source of Zhangye city and approximately 76% of the agricultural irrigation water is from this river. Therefore the situation of agricultural water used has the important influence on the water cycle of the Heihe River Basin. Thus, constructing Zhangye city into a water-saving society is very important to the sustainable development of entire river basin. Besides, the agriculture water consumption of Zhangye city occupies 95% of the total of the city, so the economization on agricultural water is the key to the construction of a water-saving society.

### 1.2.3 Yingke Irrigation District

The Yingke Irrigation District is one of the three big irrigation districts of Ganzhou Region, with 11 villages and towns, 104 administrative villages, 164,400 people, 20,960 ha. Wheat, corn and melon vegetable are the main crops.

It has a typical arid climate. In this irrigation district, the rain is scarce, the evaporation is intense and the illumination is sufficient. The annual precipitation of this region is 124.9 mm and the annual evaporation is 1291mm. There are 13 main channels (121 kilometers long), 54 branch canals (239km), 2564 field ditches (1467km), and 900 electric-pump wells. The lining rate of branch canals is 90%, and the lining rate of field ditches is 50%.

## 1.3 Changes of the water and soil resources use and the agricultural development of Zhangye City in the past years

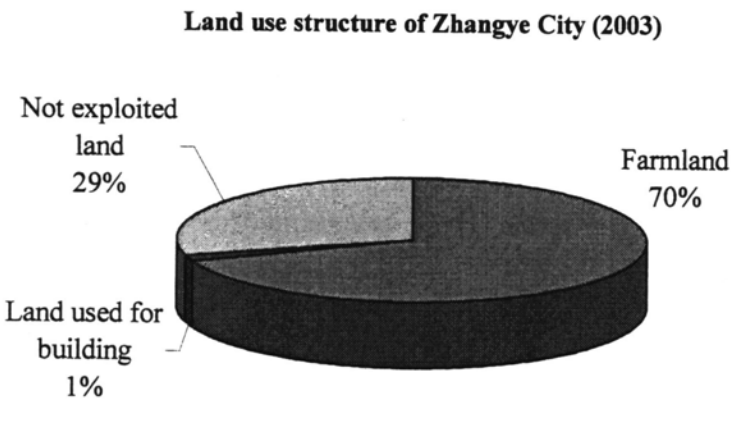


Fig.2 Land use structure of Zhangye City (2003)

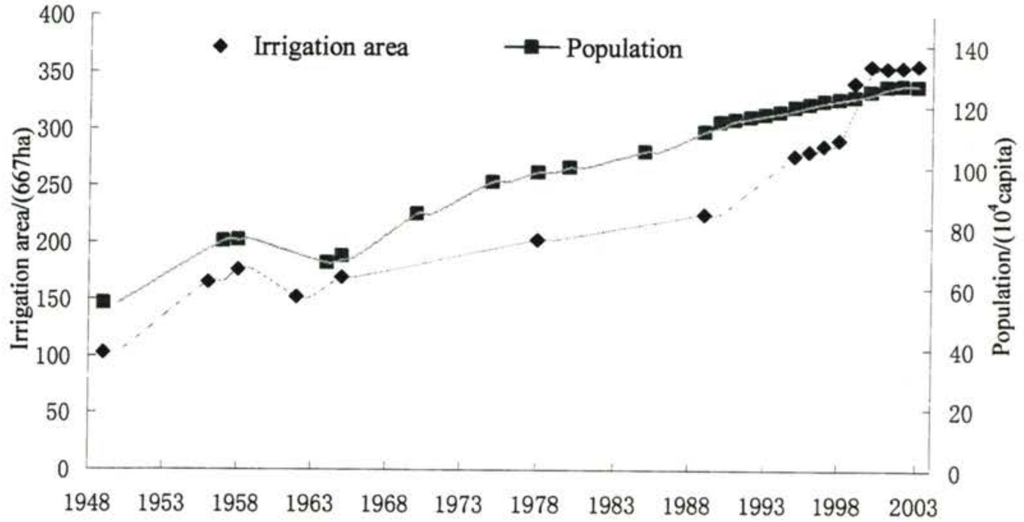


**Fig.3 Population and irrigation area of Zhangye City in the past years**

Fig.3 shows that the population of Zhangye City is 12,680,000 in 2003, 2.31 times as 5,492,000 in 1949, and the irrigation area is 237,640 ha in 2003, 3.5 times as 68,560 in 1949.

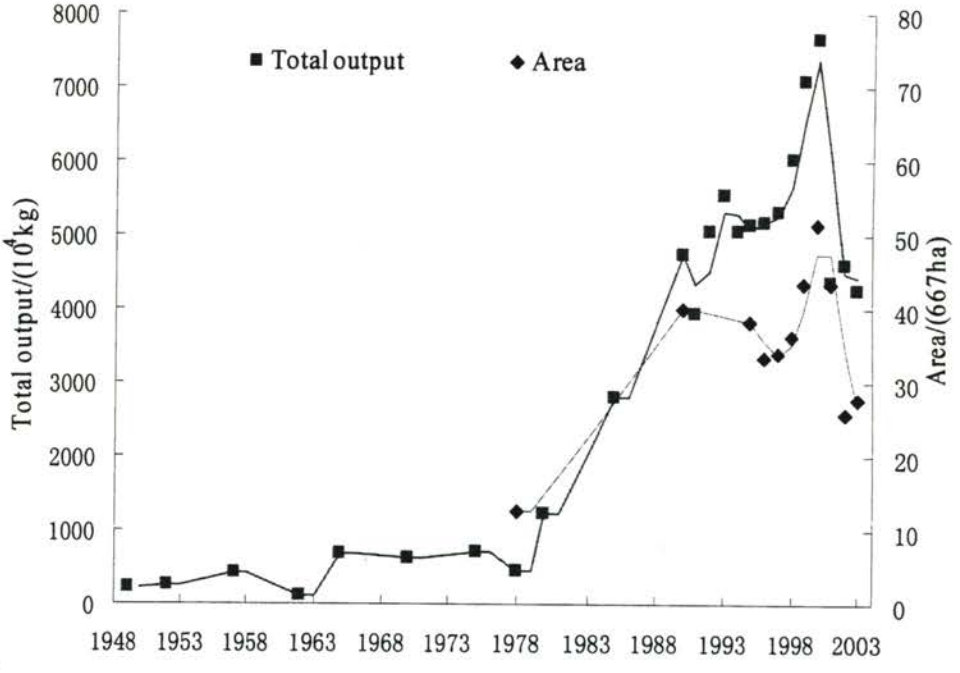


**Fig.4 Area and total output of the oil crops of Zhangye City in the past years**

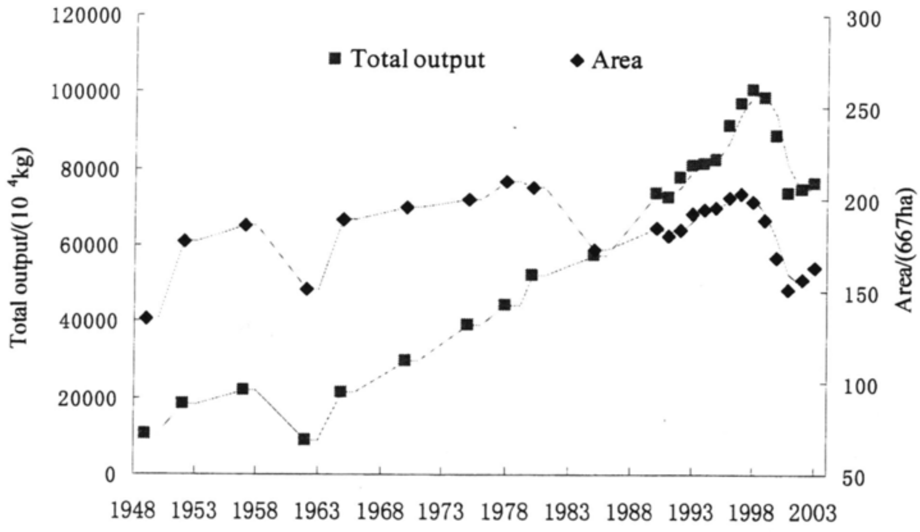


**Fig.5 Area and total output of the grain crops of Zhangye City in the past years**

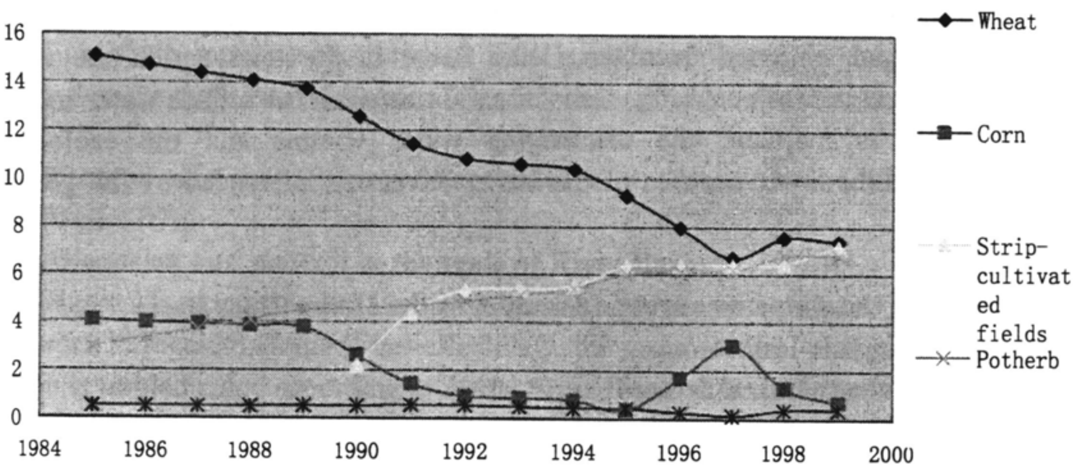


**Fig.6 Area of the crops of Zhangye City in the past years**

Since the 1980's, the areas of grain continued to drop and the areas of vegetables and other cash crops rise. The 'strip-cultivated fields' refers to wheat-maize intercropping. The research indicate the method is effective for water saving.

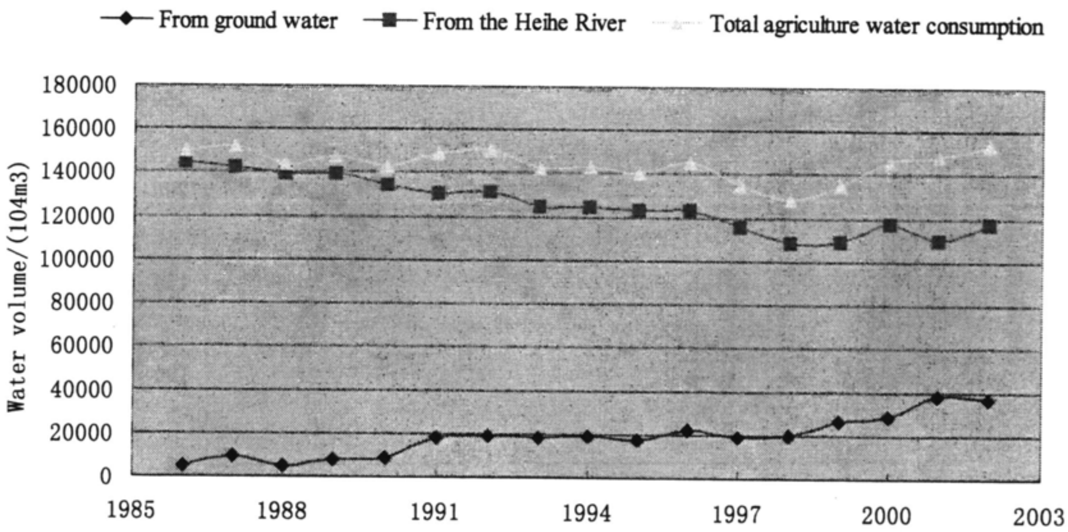


**Fig.7 Agricultural water consumption structure of Zhangye City (1986-2002)**

Fig.7 shows that the water consumption from ground water is sharply increasing and the total Agriculture water consumption is also increasing, though the proportion of the water volume obtained from the Heihe River in the total agriculture water consumption decreases. Because the transformation between the surface water and the ground water is frequent, the discharging water volume and the ecological environment of the lower reaches of the Heihe River are influenced by the ground water overdraft.

## 1.4 Problem of the water resources utilization in the Heihe River Basin

### 1.4.1 Hydro-meteorological factors

In the Heihe River Basin, with a typical arid climate, the precipitation is far less than the transpiration, the allocation of precipitation in space and time is uneven, usually concentrating in July, August and September. The least discharge of Heihe River appears in January and February. The discharge from January to March occupies 7.1% of the whole year water volume, from April to May is 11.8%, and from June to September is 68.5%. The flow of the upper reaches in May and June interrupts, about 22.4 days occupying 63% of the total days. It is the peak of irrigation water used of the middle reaches in May and June. The discharge of Yingluo Gorge occupies 20.2% of that in the whole year, but the irrigation water required in irrigation districts of the middle reaches occupies 35% of that in the whole year. Lacking key projects storing and regulating water causes to flow interrupting frequently in this period.

### 1.4.2 The unreasonable economic structure

The primary industry, secondary industry and tertiary industry of Zhangye city occupy 42%, 29%, 29% respectively (the nation is 17.6%, 49.4%, 33% respectively). The proportions of water for agricultural, industrial domestic and ecologic uses are 87.7:2.8:2.2:7.3. The output value of agriculture in the economic structure is higher than others, and the urbanization rate is low.

### 1.4.3 The hydraulic engineering construction lacking the unified plan, the random water used and the low irrigation efficiency

In the middle reaches of the Heihe River Basin, the economy is booming and the degree of water resources development is high. The massive water resources are used in the agricultural irrigation. There are 62 water intakes and 28 plain reservoirs from Yingluo Gorge to Zhengyi Gorge, so the excessive canals are crowded and disordered. And then, for these plain reservoirs the capability of storing and regulating water is low, and the transpiration rate is big. Agricultural water management is random. And the water used efficiency is low, only 0.522 in the irrigation districts of the middle reaches.

## 1.5 General Plan of the Heihe River Basin

The main contents of *General Plan of the Heihe River Basin* are: 1) to achieve the water diversion goal by closing all water intakes and draining water together; 2) to complete the plans of engineering construction, e.g. agricultural water saving plan and the water saving transformation projects of irrigation districts, including enhancing the lining rate, merging several water intakes, and stopping some plain reservoirs. It is clear that the main aim of the plan is to decrease agricultural water used.

# 2 Allocation and management of agricultural water used in the middle reaches of the Heihe River

## 2.1 Allocation and control in the scale of River Basin

(1) The macro-control water allocation according to the water allocation Scheme

In order to regulate Heihe River effectively, the macro-control plan in the entire river basin is implemented according to *Heihe River Water Allocation Scheme.* Considering the need of the production and the environment water used, the characteristic of water required in the middle and lower reaches of Heihe River, and the current condition of projects, the Scheme is approved and carried on by the State Council of the People's Republic of China. On the different guarantee rate of flow at Yingluo Gorge, the discharges of river water are controlled (Table 1). In 2002, the volume is enhanced from $8.30\times10^9 m^3$ to $9.5\times10^9 m^3$ based on the annual means volume. Water allocation scheme of water volume of Yingluo Gorge with a year can be found in Table 2.

**Table 1 Water Allocation Scheme of Zhengyi Gorge (revised in 2002) ($10^9$ $m^3$)**

| Different guarantee rate | Water volume of Yingluo Gorge | Discharging Water volume of zhengyi Gorge | Usable water volume of the middle reaches |
|---|---|---|---|
| 10% | 19.0 | 13.2 | 5.8 |
| 25% | 17.1 | 10.9 | 6.2 |
| Annual means | 15.8 | 9.5 | 6.3 |
| 75% | 14.2 | 7.6 | 6.6 |
| 90% | 12.9 | 6.3 | 6.6 |

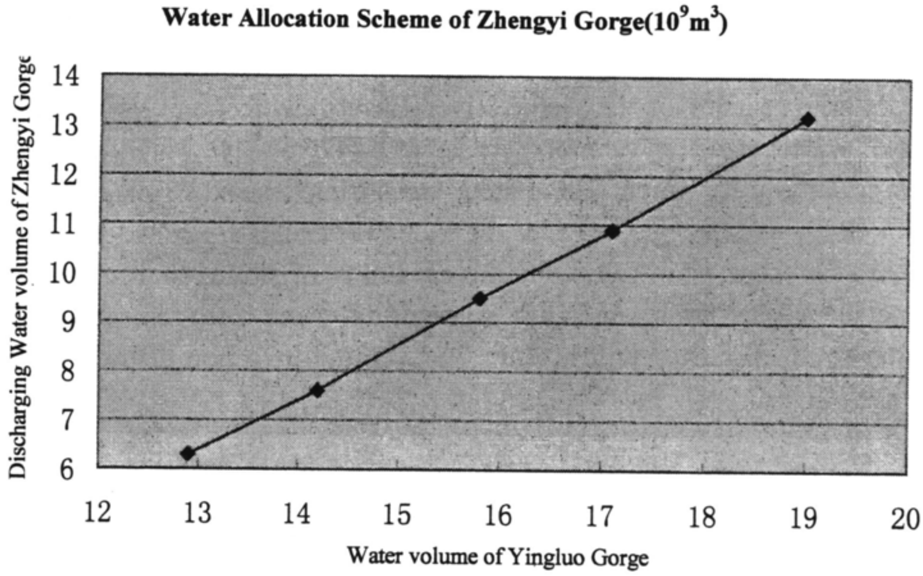


**Fig.8 Relation between water volume of Yingluo Gorge and discharging Water volume of Zhengyi Gorge**

**Table 2 Water allocation scheme of water volume and the days of water transferring of Yingluo Gorge with a year (Annual means) ($10^4$ $m^3$)**

| Items | | A year | Jan. | Feb. | Mar. | Apr. | May | Jun. | Jul. | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ① | | 158001 | 3407 | 3398 | 4247 | 6701 | 11802 | 20028 | 35083 | 31350 | 21592 | 10231 | 5937 | 4225 |
| ② | | 187 | 31 | 28 | 10 | 3 | 2 | 10 | 20 | 20 | 17 | 5 | 10 | 31 |
| ③ | | 57710 | 0 | 0 | 1913 | 4011 | 7866 | 10148 | 9461 | 8454 | 7111 | 6117 | 2632 | 0 |
| Coefficient | Loss factor | | 0.3 | 0.3 | 0.3 | 0.3 | 0.25 | 0.2 | 0.2 | 0.2 | 0.2 | 0.25 | 0.3 | 0.3 |
| | use factor | | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 | 0.95 |

①Water volume of Yingluo Gorge

②Days for water transferring

③Usable water volume of Ganzhou Region

(2) There are three time intervals of water allocation in a year as following, spring-summer irrigation period (from March 11to on June 30), summer-winter irrigation period (from July 1 to November 10) and non-irrigation period (from November 11 to March 10) (Table 3).

**Table 3 Water Allocation Scheme of Yingluo Gorge ($10^9$ $m^3$)**

| Time intervals | Different guarantee rate | Water volume of Yingluo Gorge | Discharging Water volume of zhengyi Gorge |
|---|---|---|---|
| Spring-summer irrigation period (from March 11to on June 30) | 10% | 5.6 | 2.35 |
| | 25% | 5 | 1.9 |
| | 50%(Annual means) | 3.5 | 0.75 |
| | 75% | 2.9 | 0.7 |
| | 90% | 4.25 | 1.3 |
| Summer-winter irrigation period (from July 1 to November 10) | 10% | 13.6 | 8 |
| | 25% | 10.9 | 5.2 |
| | 50%(Annual means) | 8.6 | 2.7 |
| | 75% | 7.6 | 1.6 |
| | 90% | 10 | 4.2 |
| Non-irrigation period (from November 11 to March 10) | 10% | 13.6 | 4.5 |
| | 25% | 10.9 | 4.05 |
| | 50%(Annual means) | 8.6 | 3.65 |
| | 75% | 7.6 | 3.45 |
| | 90% | 10 | 3.9 |

The total water allocation in whole year is the key guideline, and those of different intervals are only the reference standard. We can adjust the allocation quota of the same year's surplus time interval according to the total water allocation in this year.

## 2.2 Water allocation of Heihe River among different regions

There are a series of related plans and the local authority regional planning, e.g. *Water Law*, Heihe River Water Allocation Scheme and *General Plan of the Heihe River Basin*, as the disposition basis of the water allocation of Heihe river among different regions. The factor of agricultural water lacking, water used per ten thousand Yuan GDP, water used per capita, and water used per a Chinese acre are basic indexes (Table 4).

**Table 4 Water Allocation Scheme of Yingluo Gorge in the three regions ($10^9$ $m^3$)**

| Different guarantee rate | Volume of surface water resources | | | | Discharging Water volume of zhengyi Gorge | Volume of surface water resources | | |
|---|---|---|---|---|---|---|---|---|
| | Total | Heihe | Liyuanhe | Others | | Ganzhou | Linze | Gaotai |
| 90% | 16.7 | 12.9 | 2.31 | 1.49 | 6.3 | 6.25 | 3.61 | 2.48 |
| 75% | 18 | 14.2 | 2.31 | 1.49 | 7.6 | 6.25 | 3.61 | 2.48 |
| Annual means | 19.6 | 15.8 | 2.31 | 1.49 | 9.5 | 6.05 | 3.5 | 2.52 |
| 25% | 20.9 | 17.1 | 2.31 | 1.49 | 10.9 | 5.98 | 3.47 | 2.45 |
| 10% | 22.8 | 19 | 2.31 | 1.49 | 13.2 | 5.73 | 3.31 | 2.27 |

The allocation principle is as following: 1) The demand of the domestic water used and the ecology water used is firstly considered. 2) Based on the coordination of the relation between the water required and the water used in different regions, the ground water and the surface water, the local water and the transiting water are allocated together. 3) The aim is high water use factor of the life, the production and the ecology. 4) The highly effective water use is first. 5) The degrees of water lacking in different regions are approximately balanced. 6) The average water used per capita draws close gradually.

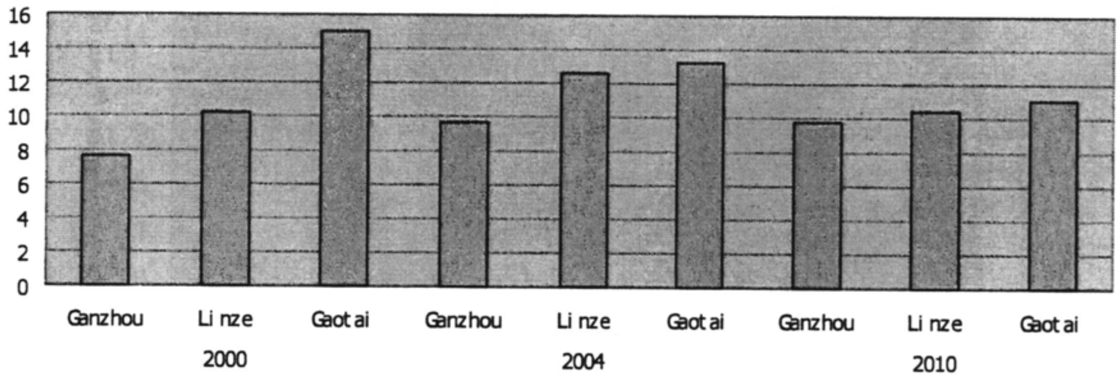


**Fig.9 Degrees of water lacking of three regions in annual means**

Fig.9 shows that the degrees of water lacking of the three regions are approximately balanced.

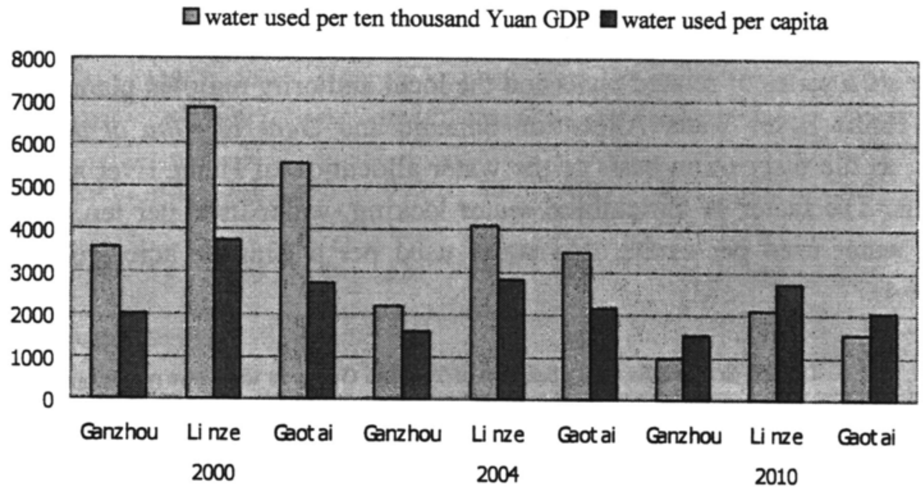


**Fig.10 Contrasts of water used per ten thousand Yuan GDP and water used per capita**

Fig.10 shows that water used per ten thousand Yuan GDP and water used per capita are all decreasing. Ganzhou's degree of water lacking is the lowest than other two countries, and its water use factor is also high, so it has the priority in water allocation.

## 2.3 Allocation of agricultural water of Zhangye City

The total water which is allocated to agricultural use of Zhangye City according to the water allocation scheme is the base to further allocate. The first step is to count the various irrigation districts. The second is to count the water demand according to quotas and water efficiency of irrigation. If the water demand is more than the estimated water supply, the crops areas should be adjusted to decrease the water demand in the scope of the water supply.

### 2.3.1 Establishment of water allocation plan (from top to bottom, taking Ganzhou as a case)

(1) Water allocation plan of Ganzhou Region

The water allocation plan is established by Ganzhou Water Resources Bureau. According to former experiences and the policies, considering the approximate irrigation areas, the frame of the water allocation plan in that year is decided by forecasting the water volume and discussing with Hydrology Bureau.

There are several essential factors considered in the establishment of water allocation plan, such as water volume forecast, the time and the days for water transferring of Heihe River. According to the above factors, the dynamic water allocation plan of each time in the whole year is established. So-called 'dynamic' refers to constantly carry on the adjustment in a month or a ten-day period according to the water volume of Yinluo Gorge.

For example, in 2004, the water volume of Yinluo Gorge is $1.58\times10^9$ $m^3$ and it is 187 days for water transferring (including non- irrigation period). So the number of days of water allocation is 178 and 9 times of rotational irrigation (including the spring, summer, fall, and winter) are planned.

(2) Irrigation plans of the irrigation districts

After investigating some basic conditions, the governors of various irrigation districts plot out the groups of rotational and continuous irrigation according to the experiences and establish the water allocation plan.

An Example - Water Allocation of Yingke Irrigation District: The total water which is allocated to Yingke Irrigation District by Ganzhou and the water allocation of each time are the base to further allocate. The balance of water supply and demand is counted and analyzed according to the irrigation areas of each time, the quotas, and water efficiency of irrigation and others. Then, the governor of Yingke Irrigation District establishes the water allocation plan.

**Table 5 Irrigation plans of Yingke Irrigation District**

| Continuous irrigation group | Rotational irrigation group | Irrigation canal | Areas (1/15ha) | | | Irrigation quota (15 $m^3$/ ha) | Net water volume in fields (15 $m^3$/ ha) | Water use factor (%) | | Gross waterdemand ($10^4$ $m^3$) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Total | River irrigation | Well irrigation | | | Branch canal | Main canal | Branch canal | Main canal |
| 0 | 0 | Main | 30520 | 22520 | 8000 | 80 | 180.16 | 59.9 | 92.4 | 300.71 | 325.58 |
| 1 | 1 | Branch 1 | 3532 | 3532 | | 80 | 28.26 | 61.8 | 100 | 45.73 | 45.73 |
| 2 | 0 | Total | 1436 | 1436 | | 80 | 11.49 | 70 | 100 | 16.42 | 16.42 |
| 2 | 2 | Lateral 1 | 1388 | 1389 | | 80 | 11.11 | 69.9 | 100 | 15.89 | 15.89 |
| 2 | 3 | Field canall | 48 | 48 | | 80 | 0.36 | 71.6 | 100 | 0.53 | 0.53 |
| 3 | 4 | Main 1 | 6477 | 3948 | 2529 | 80 | 31.58 | 59.2 | 98.2 | 53.34 | 54.32 |
| 4 | 5 | Embranchment 1(Ying) | 2159 | 2159 | | 80 | 17.27 | 59 | 98.2 | 29.27 | 29.81 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | 0 | Total | 2707 | 2707 | | 80 | 21.65 | 61.4 | 95.4 | 35.28 | 36.99 |
| 5 | 6 | Embranchment 3(Ying) | 2517 | 2517 | | 80 | 20.14 | 61.4 | 95.3 | 32.8 | 34.42 |
| 5 | 7 | Lateral 2 | 190 | 190 | | 80 | 1.52 | 61.4 | 96.4 | 2.48 | 2.57 |
| 6 | 0 | Total | 5097 | 3142 | 1955 | 80 | 25.14 | 58.6 | 95 | 42.93 | 45.19 |
| 6 | 8 | Branch 2 | 3580 | 2895 | 795 | 80 | 23.08 | 58.4 | 95.3 | 39.52 | 41.47 |
| 6 | 9 | Branch 3 | 1417 | 257 | 1160 | 80 | 2.06 | 60.4 | 91.7 | 3.41 | 3.72 |
| 7 | 10 | Embranchment 3(Ying) | 1731 | 1205 | 526 | 80 | 9.64 | 58.3 | 91.7 | 16.54 | 18.03 |
| 8 | 11 | Embranchment 4(Ying) | 1404 | 835 | 569 | 80 | 6.68 | 63.9 | 85.7 | 10.45 | 12.2 |
| 9 | 12 | Branch 5 | 978 | 716 | 262 | 80 | 5.73 | 56.2 | 77.3 | 10.2 | 13.11 |
| 10 | 0 | Total | 472 | 129 | 343 | 80 | 1.03 | 63.2 | 75.5 | 1.63 | 2.16 |
| 10 | 13 | Branch 4 | 195 | | 195 | 80 | | 52.1 | 85.7 | | |
| 10 | 14 | Lateral 3 | 277 | 129 | 148 | 80 | 1.03 | 63.4 | 75.4 | 1.63 | 2.16 |
| 11 | 15 | Lateral 2 | 4527 | 2711 | 1916 | 80 | 21.68 | 55.7 | 75.4 | 38.92 | 51.62 |

(3) Water allocation plan of Water User Associations

Water User Associations establish the water allocation plan of irrigation groups below branch canals according to irrigation plans of the irrigation districts.

### 2.3.2 Calculation of water demand (from bottom to top)

(1) Water quota of each irrigation, Irrigation water quota in whole season, Irrigation schedule

There are different indexes for water quota of each irrigation, irrigation water quota in whole season, and irrigation schedule in the arid regions and semiarid regions of China. The irrigation schedule of Yingke Irrigation District is as following.

**Table 6 Irrigation schedule of Yingke Irrigation District**

| Crops | Irrigation times | Water quota of each irrigation (15 m³/ ha) | Water quota of each irrigation (Spring and Winter) (15 m³/ ha) | Irrigation water quotain whole season (15 m³/ ha) | Irrigation time | |
|---|---|---|---|---|---|---|
| | | | | | From | To |
| Spring rye | 5 | 78 | 100 | 412 | Apr.10 | Aug.10 |
| strip-cultivated fields | 8 | 76 | 100 | 632 | May 4 | Oct.15 |
| corn | 8 | 76 | 100 | 632 | May 20 | Sept.20 |
| coarse cereals | 8 | 76 | 100 | 632 | May 20 | Sept.20 |
| Cole | 5 | 78 | 100 | 412 | Apr.10 | Aug.15 |
| Potherb | 10 | 75 | 100 | 775 | May 10 | Oct.20 |
| Fruit tree | 8 | 78 | 100 | 646 | Mar.10 | Nov.16 |
| Two crops | 8 | 78 | 100 | 404 | Aug.1 | Nov.16 |
| Forest - grass | 4 | 85 | 100 | 695 | Mar.10 | Nov.16 |

1) Irrigation Area is 15.02 thousand

2) Irrigation water quotas in spring and winter are constant.

Because rotational irrigation is the main characteristic of agricultural irrigation of Zhangye Ctity, the beginning and end time is different for various water use units (Taking Xiaoman Village as an example, Table 7).

**Table 7 Irrigation time of Xiaoman Village (From farmers orally)**

| Name of turns | Irritation object | Start stop time |
|---|---|---|
| Spring irritation i | Open area, early vegetable, forest land | Mar.20 - Apr.5 |
| Summer irritation i | Wheat | Apr.15 - May 10 |
| Summer irritation ii | Wheat, corn, fiel | May 10 - May 30 |
| Summer irritation iii | Whole area | Jun.15 - Jun. 30 |
| Autumn irritation i | Whole area | Jul.20 – Aug.9 |
| Autumn irritation ii | Whole area | Aug.15 - Aug.28 |
| Autumn irritation iii | Whole area | Sept.20 - Oct.5 |
| Winter irritation i | Fruit tree, forest-grass, open area | Oct.15 - Oct.24 |

Irrigation time of each turn of irrigation areas is the sum of each start stop time of various water use units.

(2) Crop area

The irrigation groups send the number of total areas to Water User Associations. Each Water User Association reports to the management station. Then it is send to higher-up once more. The governors of irrigation districts respectively put forward applications of irrigation water to Ganzhou Water Resources Bureau.

(3) Irrigation water

Irrigation water of each turn = $\sum$Crop areas × Water quota of each irrigation

Total irrigation water = $\sum$ Irrigation water of each turn

(4) Agricultural water

Agricultural water = Irrigation water + Water of domestic use in the country + Water of domestic animal use

Water quota of domestic use in the country = 50m$^3$/(capita· day)

Water quota of domestic animal use = 22 - 45m$^3$/(capita · day)

### 2.3.3 Actual operation and adjustment

The methods described as above are usual and the same to those of every year. The main procedure is to adjust little according to the actual situation.

The three months of December, January, and February are the non-irrigation season, so the water volume wouldn't be forecasted. The water volume of the period from April to November can be calculated by the partition computation method.

The water volume in March is little, so various irrigation districts take the water according to the area proportions.

The water volume of the period from April to November is more, so that of the second quarter can be forecasted by the actual water volume in March. The rest may be deduced by analogy.

Finally usable water volume of one year can be calculated according to the coming water. Various irrigation districts can get their water based on the area. In order not to surpass this target of water supply, the water volume on each month and each ten-day period should be adjusted little.

For example, in 1993, weather forecast is as following: dry in the end of spring and the beginning of summer, normal and few in August, few from September to November.

According to this forecast, the frequency of the three periods which are from April to June, from July to August, and from September to November is forecasted, 75%, 50%, and 70% respectively.

## 3 Irrigation Management System in Yingke Irrigation District

### 3.1 Management organization

The management organization consists of water management organization and water user organization (Fig.11)

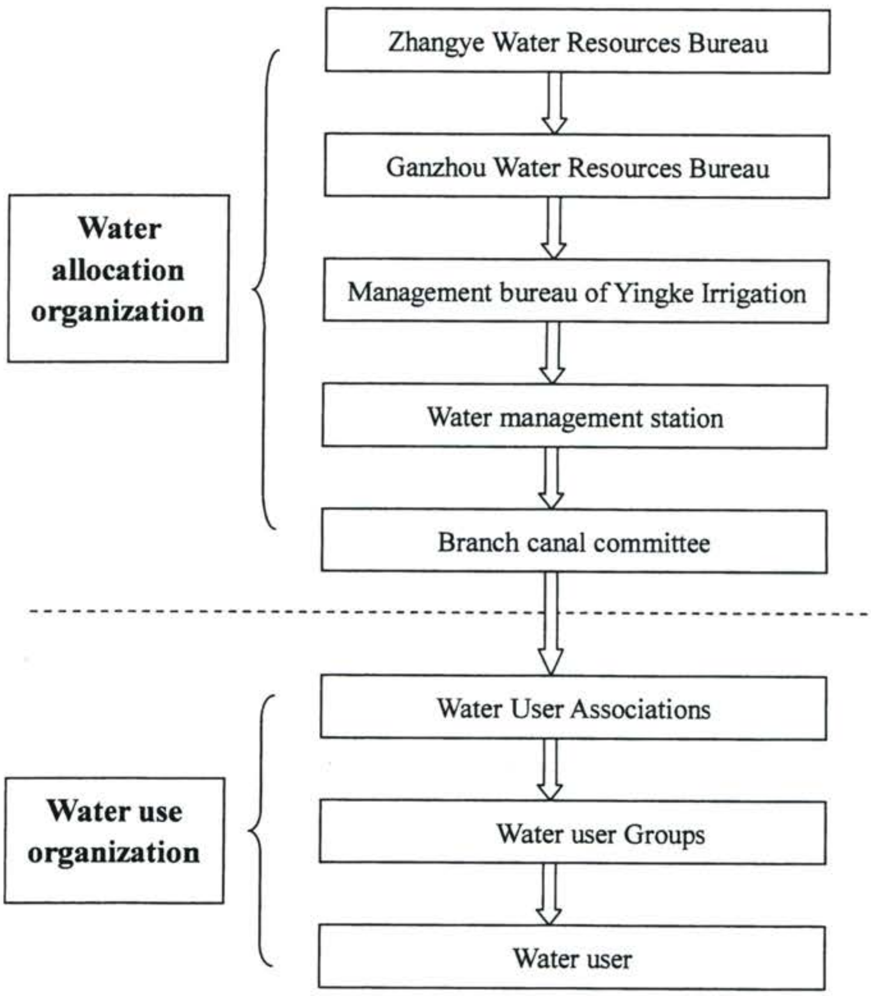


**Fig.11 Management organization in Yingke Irrigation District**

The management bureau of Yingke Irrigation District is one of the organizations of

Ganzhou Water Resources Bureau. The management station is established according to townships or towns. Branch canal committee consists of 2-3 committees. Above makes up of the water management organization. The organization below Water User Associations consists of water users. Branch canal committee is responsible for allocate the water to each lateral canal.

Water User Associations are responsible for establishing the water allocation plan, adjusting the allocated water among water use groups, dealing with disputes, and the maintenance work below the lateral canal. Water use groups are responsible for the water allocation below the lateral canal.

### 3.2 Water use management

#### 3.2.1 Surface water resources management

(1)Water level management and water volume management: There are 34 personnel responsible for the measure work in main canal, branch canal, and lateral canal. The data are the basis for the adjustment of water allocation.

(2) Water allocation duty in the irrigation area: Above the lateral canal, the personnel of the management bureau are responsible for the water allocation duty. Below the lateral canal, it is the duty of Water User Associations.

(3) Water right license: Each farmer household has the water rights license and pays fee according to it.

(4) Water charge: If the water use is not exceeding the water quota, the water charge consists of two parts which is the basic water charge and the measurement water charge.

The basic water charge is 30 Yuan per ha, and the measurement water charge is 0.85 cent per $m^3$ (1 Japanese Yen per $m^3$).

#### 3.2.2 Wells water management

In 2004, the total area of Yingke Irrigation District is 13,140 ha, including the well irrigation area, 3,467 ha, approximately occupying 25% of the total area. There are three types, river irrigation area, well irrigation area, and mixed water irrigation area. Therefore when wells are finished, the water use permission license is given by the water administration department after checking and accepting. The man in charge sends the water use plan very month. After the plan is approved, it would be in effect. There is a water meter for each well. The water volume is measured by brushing the card in several wells.

Water charge: The basic water charge is near 210 Yuan per ha. The electrical bill, the management service fee and the electromechanical device maintain fees are paid by the beneficiary.

### 3.3 Project management

The management bureau of Yingke Irrigation District is responsible for the maintenance and management of the irrigation projects above the branch canal. And Water User Associations are responsible for those below the lateral canal.

## 4 Measures, effects and problems of the construction of Water-Saving Society in Zhangye City

### 4.1 Measures for construction of the water-saving society

1 ) Control of total water consumption, management of quotas, and estimation of crops on the basis of water consumption. According to the water allocation plan for the Heihe River decided by the State Council, a fixed volume of water is allocated to the lower reaches. The available volume of water resources is allocated to each county, to each township, and finally to each village. The quotas for domestic, industrial, agricultural, and ecological uses are formulated and basic prices fixed. The actual irrigated area in 2000 taken as the basis, initial water rights are allocated. The total volume of water consumption is checked based on the quotas, and, if the total volume is deficient, the structure of crops is adjusted. Water consumption within the quota is paid for on the basic price basis; water consumption exceeding the quota is paid for on an additional price basis: for water consumption exceeding the quota by 1%-3%, additional 50% of the basic price is paid, exceeding the quota by 31%-50%, 100%, and exceeding the quota by 51% or more, 200%.

2 ) Public participation and water allocation to each family. Water users' associations are set up, participating in the supervision of water rights, water prices, and water consumption. The associations break soon the total volume and distribute it to each piece of land for each round of irrigation. On this base, the responsible department issues water right license to the farmers.

3 ) Supply by ticket and trade of water. The farmers buy water from water management institutions with the license for each round of irrigation and the water management institutions charge them on the basis of the fired prices. Surplus water can be sold, and the buyer and seller can negotiate over the price within the range of government's guiding price. The water users' associations (WUA) coordinates water supply.

Ordinary water meters are generally used to control the water volume in most well irrigation areas. And up-front cash cards are used to in several areas based on water right and volume pilot tests. When farmers put their cards on the card reader, water is started to supply. After farmers take back their cards, the card reader automatically writes down the water volume. The cost of this equipment is very high, so it isn't possible used widely in current situations.

The above measures make up of the water-saving mechanism. Through the measures of control of total water consumption, management of quotas, and distributed water to households, the water rights system in regions is established. Supply by ticket and trade of water, control of total water consumption, water charge levy truly become the main tools for construction of the water-saving society.

### 4.2 An Example of Implementation – Liyuanhe Irrigation District

The Liyuanhe Irrigation District is a large irrigation district of 20,000 ha on the middle reaches of the Heihe River. The construction of the water-saving society began in 2001, and the year of 2003 witnessed the following preliminary effects.

1) WUA had been popularized. 45 water users' associations had been set up, and

10,680 licenses had been issued. Farmers' awareness of using water, managing water, and saving water had been enhanced.

2) The agricultural structure had been successfully adjusted. The grain crops-economic crops-forest and grass proportion for 2000 was 56:14:30, while the proportion 2003 is 22:46:32. This adjustment only helped save 5,700,000 $m^3$ of water and increase farmers' income by 2101 Yuan per person on the average. The farmers had also changed, from passively accepting adjustment to actively adjusting the structure of crops according to economic benefit and market demand (Table 9).

3) The efficiency and benefit of water resource utilization had been raised. The net irrigation quota had decreased from 1275 $m^3$/ha to 1200 $m^3$/ha, and the utilization rate of the canal system had increased from 0.49to 0.54. The volume of water diverted for the irrigation area in 2003 decreased by 25,000,000 $m^3$.

4) The load of water fee had been lowered. The agricultural water fee had reduced by 105Yuan/ha, and the rate of water fee collection had increased obviously.

### 4.3 Conclusions and Discussions

1) The construction of the water-saving society at Zhangye has yielded significant effects, and it has helped the fulfillment of the plan of water allocation to the lower reaches.

2) Although water consumption is restricted and water is saved, both farmers' income and social productivity have been raised.

3) A whole set of effective ways has been found out for the operation of water rights and water markets. The previous system of governmental control is initially transformed into the system control

4) The water volume to the lower reaches of the river is increased and the ecological environment is improved.

**Table 8 Achievements of water transfer projects in the Heihe River (2000-2004) ( $10^8$ $m^3$)**

| Year | Water transfer indexes (Water volume of Yingluo Gorge is $1.58\times10^9m^3$) | Actual water volume | Discharging water volume of Zhengyi Gorge |
|---|---|---|---|
| 2000 | 8.0 | 14.62 | 6.50 |
| 2001 | 8.3 | 13.13 | 6.39 |
| 2002 | 9.0 | 16.11 | 9.23 |
| 2003 | 9.5 | 19.00 | 12.55 |
| 2004 | 9.5 | 14.98 | 8.55 |

Some problems need to be further studied.

1) Saving water is an effective way to alleviate the pressure of water shortage; however, it cannot solve all the water-related problems.

2) The construction of a water-saving society is a gradual process, and it needs long-term efforts. For example, great efforts must be made to better water users' associations and to bring their functions into full play.

3) A water-saving society must be sustainable, and thus it needs to be supported by regulations and mechanism. For example, the mechanism of compensation for saving water should be established and enforced; otherwise, the effect of saving water in the irrigation area would be in inverse proportion to the income and the enthusiasm for saving water would be affected. If things go on like this, the effect of saving water would be ruined.

4) The pilot construction under study was supported by the state policy and state input. Nationwide popularization needs both financial support and policy support.

5) Because the integrated management of surface water and ground water is not considered into the former design of the water-saving society, the water consumption from ground water is sharply increasing instead when the water volume obtained from the Heihe River is decreasing. So some watershed forests are dying down and the ecological environment of the lower reaches of the river is getting worse. How to scientifically transfer water taking account of the ecological environment of the middle and the lower reaches needs to be further studied. At present the governors of Zhangye City are applying for reducing the discharging water volume to Ministry of Water Resources of China.

6) Because the control projects along the Heihe River are extremely lacking, it is very difficult to supervise the work of closing all water intakes at the same time. Therefore the departments and grassroots units often complain.

# A hydrologic model for simulating the historical change of water resources in the Heihe River Basin during these two millennia

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## 1. Introduction

The Heihe River (130,000 km$^2$) is one of the largest inner river in China and shows a various aspects. The climate in the lower reach of the basin is very arid so that most part of the region is desert. In the middle reach there are many oases and crops land. Forest zones extend in the upper region and in high mountain area there are no plants and are some glaciers. The glacier and seasonal snowmelt in the high mountain area mainly feed mid and lower reach of the river.

Water resources in the Heihe River has been changed due to climate change and human activities, such as irrigation and domestic water use, and change of land use during these two millennia. Especially a drastic change has occurred in the last five decades mainly due to human activities. The overuse of river and ground water causes the water shortage, shrinkage the lakes and desertification in the lower reach region. It is very important for sustainable development in this region to establish the sustainable water management policy for the whole basin. In order to establish the policy, it must be clarify and access how the climate change and human activities affect the water resources in these 2000 years through the hydrologic simulations.

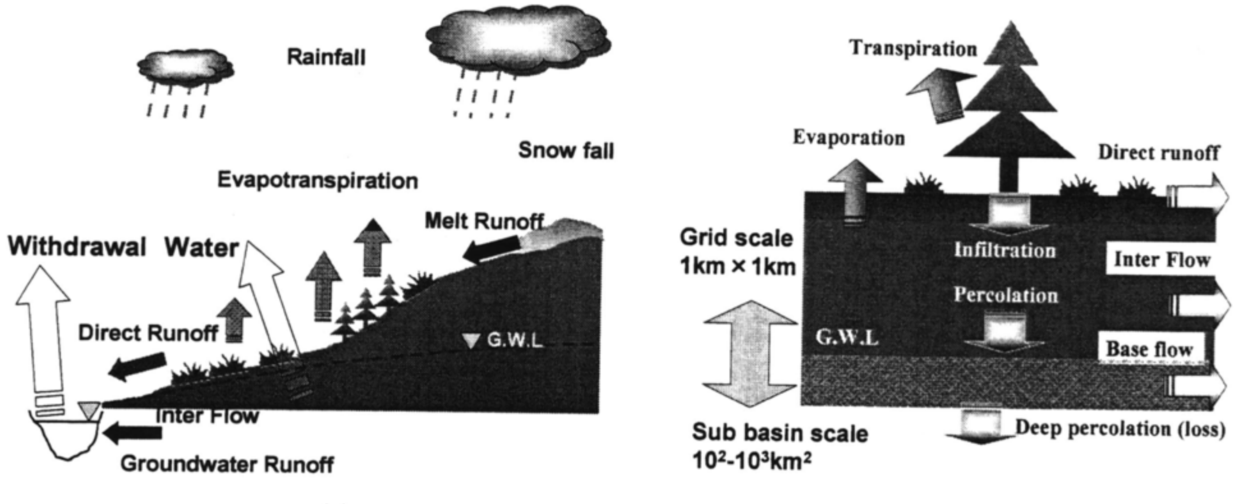
In order to achieve the purpose, a grid based process oriented semi-distributed physical based hydrologic model capable of handling the effect of change of land use and over use of groundwater and river discharge in the basin has been developed. The required input variables are limited two data, precipitation and air temperature because only these data can be reconstructed by some methods, such as ice core ,tree ring and lake sedimentation analysis. Model input such as, slope, azimuth, flow direction are generated using DEM (digital elevation model) and GIS (geophysical information system).

## 2. Model description

The model structure is designed to provide a representation of main hydrological processes occurred in the basin at the topographic scale described by digital elevation data (1 km x 1 km grid spacing). It includes a evapotranspiration model based on Penman-Monteith approach, an energy balance model for snow accumulation and melt, a two soil layer model (rotting zone and below the rooting zone), and a saturated subsurface and base flow model. The elements of the water budget in the model and the water balance of vegetation and rooting zone for a model grid cell are shown in Figure 1,(a) and (b).

The simulated soil water balance equation for an individual cell is written as

$$\frac{dS}{dt} = (P - Q_d) - Q_i - E_t - Per \tag{1}$$




(a) (b)

Figure 1. Model representation.(a) Elements of the water budget in the model, (b) Vegetation and rooting zone water balance for a model grid cell.

where S the soil water storage in the rooting zone, P the precipitation, $Q_d$ the direct runoff, (P - $Q_d$) the infiltrated water in to the rooting zone, Qi the inter flow, Et the evapotranspiration from the rooting zone, Per the percolated water in to the layer below the rooting zone.

2.1. Direct runoff

Direct runoff occurs when the precipitation excess the soil moisture deficit of the uppermost layer of the rooting zone. The soil moisture deficit $F_m$ is defined as

$$F_m = D_s(\phi - \theta) \tag{2}$$

where Ds the thickness of the uppermost layer of the surface soil, $\phi$ the soil porosity, $\theta$ the volumetric soil moisture content. If P exceeds $F_m$, direct runoff will occur and will be equal to (P – $F_m$). The thickness Ds is obtained through calibration. As shown later, in the un-calibrated simulation the initial value of 0.3m is assigned for all grid cells.

2.2. Inter flow

If the infiltration rate is larger than the evapotranspiration rate, the water content in the rooting zone may eventually exceed the field capacity, and some of the infiltrated water may appear again on the surface as interflow. The fraction $\beta_i$ of the excess soil water which appears on the surface is calculated as

$$\beta_i = \frac{0.058\, K_S\, S_0}{\phi} \tag{3}$$

where $K_S$ the saturation hydraulic conductivity, $S_0$ the overland slope of the grid cell. In the derivation of equation (3), the area of grid cell is 1 $km^2$ and a length of stream in a grid cell is assumed to be 1.414 km.

The volume of percolated water are based on an average soil moisture conditions during the time step, $\Delta t$. The volume is calculated via Darcy's law assuming a unit hydraulic gradient:

$$Per = \frac{K_v(\theta) + K_v(\theta^*)}{2}\Delta t \tag{4}$$

where $K_v(\theta)$ the soil vertical unsaturated hydraulic conductivity and calculated by Brooks-Corey equation by setting the exponent equal to 3, $\theta^* = \theta + (P - Q_d)/D_r$.

2.3. Evapotranspiration

Potential evapotranspiration $E_p$ is estimated using Penman-Monteith equation and actual evapotranspiration $E_t$ is a function of soil moisture and estimated from the relationship

$$\frac{E_t}{E_p} = \begin{cases} 1 & \theta \geq \theta_f \\ \dfrac{\theta - \theta_w}{\theta_f - \theta_w} & \theta_w \leq \theta \leq \theta_f \\ 0 & \theta \leq \theta_w \end{cases} . \tag{5}$$

where $\theta_f$ is the soil water content at a field capacity, $\theta_w$ is the soil water content at a wilting point.

2.4. Base flow

Similar to interflow, base flow is also a contribution of the percolated portion of the precipitation to a stream. To calculated base flow, it is assumed that the horizontal subsurface flow follows Darcy's law with the hydraulic gradient set to equal the average over land slope of the sub-basin. Base flow is calculated as

$$Q_g = \frac{1.44 L \hat{K} S_b}{\phi_b A} D_{br} \phi_b \tag{6}$$

where L the total length of streams in the sub-basin, A the area of the sub-basin, $\hat{K}$ the unsaturated hydraulic conductivity, $\phi_b$ the porosity of the layer below the rooting zone, $D_{br}$ the thickness of the layer below the rooting zone, $S_b$ the average slope of the sub-basin.

2.5. Snow melt

The partition of precipitation into rain or snow is based on critical air temperature:

$$\begin{aligned} &P_s = P && T_a \leq T_{\min} \\ &P_s = \frac{T_{\max} - T_a}{T_{\max} - T_{\min}} && T_{\min} < T_a < T_{\max} \\ &P_s = 0 && T_a \geq T_{\max} \end{aligned} \tag{7}$$

$$P_r = P - P_s \tag{8}$$

where $P_r$ and $P_s$ the water equivalent depth of rain and snow, respectively, $T_{\min}$ the lower critical air temperature below which all precipitation is in the form of snow, $T_{\max n}$ the upper critical air temperature above which all precipitation is rain. In this study the typical values -1.1 ℃, 3.0 ℃ are assumed.

The snowpack energy balance is given by

$$c_s W \frac{dT_s}{dt} = R_{ns} + Q_s + Q_l + Q_p + Q_m + Q_g \tag{9}$$

where $c_s$ the specific heat of ice, W the water equivalent of the snowpack, $T_s$ the snowpack temperature, $t$ is time, $R_{ns}$ the net radiation, $Q_s$ the sensible heat flux, $Q_l$ sensible heat flux, $Q_p$ the heat advected to the snowpack by rainfall, $Q_m$ the latent heat flux, $Q_g$ heat conduction from the snow-soil interface. Fluxes into the pack are taken positive. Heat conduction from the snow-ground interface is neglected. The left-hand term in equation (9) is the change in snowpack cold content. The change in snowpack temperature at the end of time step is calculated by

$$T_s^{t+\Delta t} = T_s^t + \frac{\Delta t}{c_s W}\left[R_{ns} + Q_s + Q_l + Q_p + Q_m\right] \tag{10}$$

When the snowpack is isothermal at 0 ℃, the heat flux for snow melt is calculated by

$$Q_m = R_{ns} + Q_s + Q_l + Q_p + c_s W T_s^t \tag{11}$$

The sensible and latent heat fluxes are given by

$$Q_s = \frac{\rho c_p \left(T_a - T_s\right)}{r_{as}} \quad (12), \qquad Q_l = \frac{\lambda \rho \left[\frac{0.622}{P_a}\right]\left[e(T_a) - e_s(T_s)\right]}{r_{as}} \tag{13}$$

where $P_a$ the atmospheric pressure, $\lambda$ equals the latent heat of vaporization.

Water is removed from the pack when the liquid phase exceeds the current liquid water storage capacity of the snowpack taken equal to 0.06W. The depth of melt water removed from the pack per unit area is given by

$$M_p = W_{liq}^{t+\Delta t} - 0.06W^{t+\Delta t} \qquad M_p > 0 \tag{14}$$

### 3. Model application

The model was applied to the upper Heihe River basin (Figure 3). This 35,634 km$^2$ catchment ranges in elevation from 1280 m at the Zhengyixia ($99°28'E, 39°49'N$) to over 4900 m in the

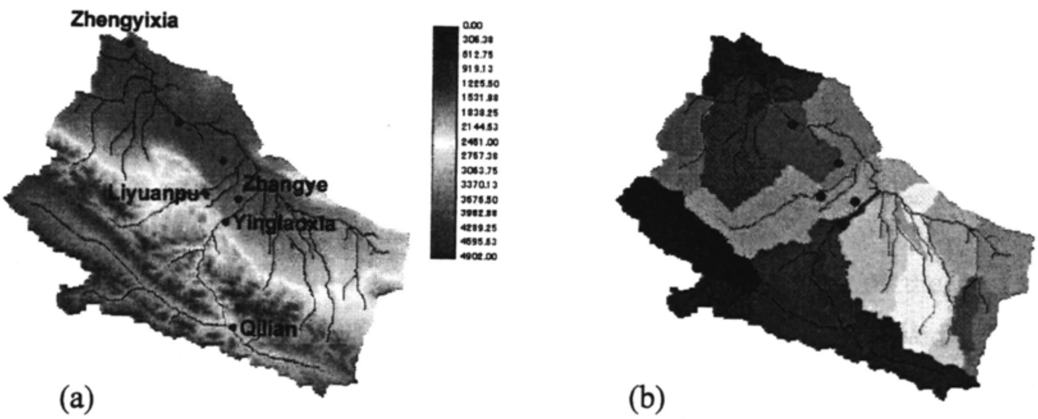



Figure 2 Map of the upper Heihe River. (a) the distribution of elevation and false channel network, (b) 27 sub basins divided by using the watershed module of GIS

Qilian mountains. There are three hydrological stations, Qilian ($100°14'E, 38°12'6'N, 2{,}590m$), Liyuanpu ($100°00'E, 38°58'N, 1{,}626m$) and Yinglaoxia ($100°11'E, 38°48'N, 1{,}674m$). The catchments areas at these three stations are 2,452 km$^2$, 2,240 km$^2$ and 10,009 km$^2$, respectively. The basin was divided into 27 sub basins by using the watershed module of the geophysical information system Kilimanjaro.

Precipitation increases with elevation and the used relationship between an annual precipitation and elevation as follows:

$$P_Z = 460 \cdot \log_{10}(Z) - 3250 \tag{15}$$

where $P_Z$ the annual precipitation at elevation Z (m) , Z is elevation (m). The air temperature at the height Z in meters is estimated by using the lapse ratio as follow:

$$T_{aZ} = T_{a0} - \gamma(Z - Z_0)/100 \tag{16}$$

where $T_{aZ}$ is the air temperature at the elevation Z (m), $T_{a0}$ the air temperature at the gauging station, $Z_0$ the elevation at the gauging station in meters. The used raps ratio of each month is shown in Table 1.

Table 1 Seasonal variation of the laps rate

| Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.33 | 0.43 | 0.51 | 0.57 | 0.61 | 0.63 | 0.63 | 0.61 | 0.58 | 0.52 | 0.45 | 0.35 |

unit:℃/100m

The model was run at a daily time step over a DEM with 1 km grid spacing for direct runoff, inter flow, evapotranspiration and snow accumulation and its melt, and run at a monthly step over sub basin for base flow. Daily values of precipitation and air temperature were available from Zhangyie station ($100°23'E, 38°56'N, 1{,}483m$). Clear-sky solar radiation was calculated for each grid cell prior to the model run using the algorithm accounting for the date, grid cell location, slope, and aspect.

The spatial distribution of land use was estimated using a global land cover characteristics for simple biosphere 2 model produced by USGS. Each grid cell was assigned one of the following cover types: broadleaf evergreen trees (Class 1), broadleaf deciduous trees (Class 2), broadleaf and needle leaf trees (Class 3), needle leaf evergreen trees (Class 4), needle leaf deciduous trees (Class5), short vegetation/ C4 grassland (Class 6), shrubs with bare soil (Class7), dwarf trees and shrubs (Class 8), agriculture or C3 grassland (Class 9), water, wetlands (Class 10), ice/snow (Class 11) (Figure 3).

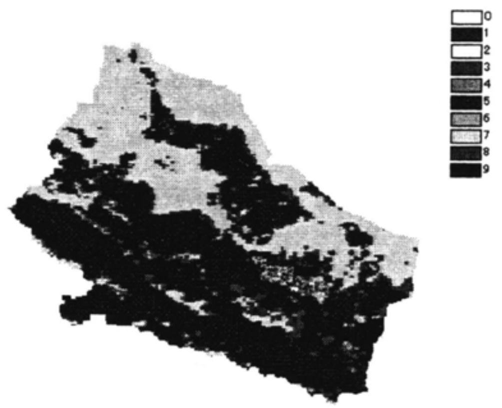



Figure 3 Map of the distribution of land use of the upper Heihe River.

The values for vegetation and soil parameters and other parameters used in the un-calibrated simulation are presented in Table 3.

Table 3 Model parameters of each land use class

| Parameters | Class 6 | Class 7 | Class 8 | Class 9 |
|---|---|---|---|---|
| Ds(m) | 0.2 | | | |
| Dr(m) | 1.0 | | | |
| $D_{br}$(m) | 3.0 | | | |
| $\phi$ | 0.45 | | | |
| $\theta_r$ | 0.30 | | | |
| $\theta_w$ | 0.009 | | | |
| $K_S\left(m \cdot h^{-1}\right)$ | 0.2 | | | |
| LAI | 4 (Trees), 1.3(grass and crops) | | | |
| F | 0.5 | 0.2 | 0.5 | 0.5 |
| $r\min x\left(m^{-1}s\right)$ (Trees) | 200 | | | |
| $r\max\left(m^{-1}s\right)$ (Trees) | 2000 | | | |
| $r\min\left(m^{-1}s\right)$ (Grass and Crops) | 200 | | | |
| $r\max\left(m^{-1}s\right)$ (Grass and Crops) | 2000 | | | |
| $r_a\left(m^{-1}s\right)$ (Soil surface) | 80 | | | |
| $r_{snow}\left(m^{-1}s\right)$ (Snow surface) | 100 | | | |

The un-calibrated poor simulation results at three stations for September, 1994 – August, 1998 are shown in Figure 4. Such poor results were inevitable results because model parameters ware not calibrated. These results show that the used relationship between precipitation and elevation should be improved. Namely, results show that not only annual precipitation but frequency of precipitation increases with elevation. However the un-calibrated model simulates a seasonal variation of stream

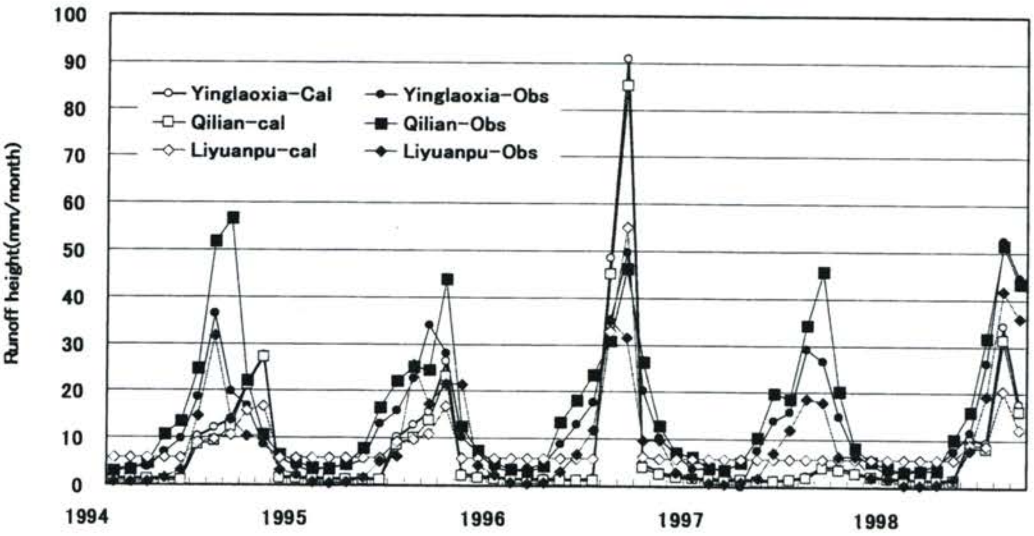



Figure 4 Simulated and recorded stream flows for September, 1994- August, 1998 at three stations. The model was un-calibrated.

flow roughly. It shows that if model parameters are adjusted and a better method to estimate a time and spatial distribution of precipitation is established the model can simulate well stream flow.

## 4. Concluding remarks

A physically based semi distributed hydrologic model for simulating the change of water resources during 2000 years. The model includes main hydrological processes occur in the basin, such as direct runoff, interflow, infiltration, percolation, evapotranspiration and snowmelt. Digital elevation model and GIS are used to model important topographic controls on incoming solar radiation and the false channel network.

The model took about ten minutes for one year simulation at a spatial resolutions resulting in $O(10^4)$ pixels on WindowsXP PC with CPU Pentium 4, 3.4 GHz (e.g., Dell Dimension8400). It may need two weeks for 2000 years simulation for upper Heihe River basin, and more than 20days for whole basin simulation. The model must improve and/or simplify to reduce computation effort.

As with all models of this type, the availability of spatially distributed data for model input and watershed characteristics, such as soil and vegetation parameters, are limited. Improved model performance will require a better estimation method of time and spatial distribution of precipitation, air temperature and wind speed.

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# The Struggle for Water in the Heihe River Basin:

## Towards Understanding the Social Dimension

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I am one of the core members of the Oasis Project, and I lead the team of anthropologists and sociologists in this project. We have divided the Heihe river basin into three areas: upper, middle and lower, and the area of middle reaches are divided into two areas conceptually. One is the old oasis area and the other is a newly exploited area in much more arid zone. Our members have studied each of these areas and have tried to understand how the local people live and how they rely on the natural resources. We have focused on water which is limited in this area and is a source for many conflicts. The following four reports will provide details on the relationship between ecological aspects and the human activities, but here I would like to say something about the social dimension.

I went to the Ejina banner for the first time in 2000, before the start of this project. And since that I have been there 4 times and interviewed some old men and women. My colleague Mrs. Sarangerel has transcribed these interviews and we have just translated into Japanese 9 old women's interviews. I hope to reconstruct the history of this area by using these texts.

In general the study of life-history is focused on the individual cases. And it is more important to analyze how things are narrated rather than how they have happened. In such a research, it is usual for the researcher to stay stoic and not to add or cut any words. However, we must recognize that life histories also contain valuable information which is unavailable in written sources. Since task is to reconstruct the history of this region, especially the history of the natural environment of this region, I want to make some general observations based on these individual texts.

### 1) Tribal identities of the informants

4 of the 9 women are Khalkha. Khalkha is one of the Mongolian tribes and live in central area of the Republic of Mongolia. 3 were born in 1921, 1930 and 1940, respectively, in what was then called the Mongolian People's Republic (MPR). And the fourth was born in the Ejina banner of Inner Mongolia in 1936 into a family who had

migrated form the MPR.

I do not know the exact figure of the Khalkha Mongolis in the Ejina banner. I can only say that many descendants of the Khalkha are living in this area. Many people have moved south to escape the communist revolution in Outer Mongolia in 1921. Most fled the MPR to the south in 1937 and 1938 when a great purge was conducted against Buddhist monks and the wealthy families. Until 1945 when the border was closed, people were relatively free to come and go between the MPR and Inner Mongolia. The Ejina banner area is strategically very important in the present as in the past two thousand years.

The rest of the informants are Torgut, a Mongolian tribe now dispersed in several countries: the Volga region of the Russian Federation, the western provinces of the Republic of Mongolia, and the Xinjiang Uyghur Autonomous Region of China.

## 2) The Landscape of Childhood

Our interview materials contain a lot of information about the landscape of the region as remembered by these women when they were children. This remembered landscape constitutes a moral and political commentary on the ecological change in the region.

### *2-1) Reed*

Many women talked about the reed grew near the bank of rivers and lakes. The height of the reed was nearly 3 meters, enough to hide a man riding camel. People used to hear the sound of the bells tied on the camels but could not see them. Today, there is not much reed left, which is a clear indicator that the natural environment has changed.

### *2-2) Fishes in the memory*

Old women loved to talk about fishes. When they were children, they used to play near rivers or lakes. And they were taught by elders not to play with fishes. After their conversion to Tibetan Buddhism, Mongols admire fish as the symbol of knowledge, for it has no eyelid and never closes its eyes. So the death of fishes because of the lack of water is interpreted as the death of knowledge and the death of their culture.

### *2-3) Trees in the landscape*

Most of these old women have not much knowledge about plants and talked little. But one woman was able to mention 17 kinds of plants and to give explanation about their characteristics and how to use them for human and animals. Almost all of the old women interviewed made a reference to two kinds of trees, *jigd* and *tuurai*. *Jigd* is a kind of the oleaster and *tuurai* is a kind of poplar and is famous in this arid zone.

The distribution of these trees is now different from the old time. In the old days *jigd* trees grew mostly along the west river called the Moron, and less along the east river called the Ejina. We can now see a lot of planted *jigd* trees along the east river. The Mongolian word Moron means a big and wide river. So it is natural that trees which like water grow much more along the big river.

In these old green belts there were still many birds singing including many kinds of owl, just only in memories.

***2-4) Special tree in the landscape***

Nowadays the main kind of vegetation in this banner is the tamarisk called *sohai* in Mongolian. It is abundant, and the local knowledge about this plant is wide spread. People would say, for example, it "in a year twice comes into flower", or "after the rain camel eats the flower to death" etc. They told us that this plant has spread wider and wider recently.

In Mongolian language *sobai* means being infertile, and the name of the tree *sohai* sounds like *sobai,* implying infertility of the land.

**3) Old and New Migration**

The Ejina banner is famous for its military site as it has been for over 2000 years, as mentioned above. In the 1950s people were forced to move into towns or farms to make room for military base. So when the old people were asked to talk about their old days in the northern, lower region, they would often talk about their memories of the southern upper region.

Nowadays, people migrate within the banner, too but for different reasons. They evacuate their pastures to grow trees or let the grassland to rejuvenate. This new practice is called "environmental migration" which is a government policy to make people move willingly or unwillingly for the reservation of natural resources including the mining resources.

About this new policy we had held two international symposia in Beijing, and we have published two books in Japanese and in Chinese. You will hear more about these in the following reports.

**4) The Cultural Revolution**

The Cultural Revolution was carried out all over China, through with uneven intensity from region to region. One of the regions severly affected is Ejina. Many Khalka Mongols were suspected to be spies of the MPR. And the Torgut Mongols, descendants of the returnees from the Volga region in the $18^{th}$ century, were as accused of being separatists. So in this region almost all of the Mongols became the lowest class of indeed enemies. Every old women and men, regardless of their class status, would tell you about their miserable suffering during this hysterical period.

Thus, the change in the social environment in the banner has been more dramatic and severe than that in the natural environment. Revolution in ancient China meant only dynastic change, which usually left the social structure intact. Although the Cultural Revolution was intended to carry out social revolution overthrowing the upper class, in Inner Mongolia it became a revolution against the ethnic Mongols.

### 5) Adoption

Interviewing old Mongolian women about child rearing was a difficult experience. In our interviews, adoption transpired as an important practice in the region. Each of the 9 old women has experienced some form of adoption. In one case, a woman lost her first baby but she later adopted 2 children. And her husband was the adopted son of a rich man. In another case, a woman's mother was adopted by her uncle. One of her 8 children was given to her sister who was in turn also adopted.

In a society in which there is inadequate medical service and social welfare, people ofen invest in children as a safety network. Adoption may thus be understood as an effective system of redistributing human capital, a way to build a tight social network. In this region, we can see many old women live happily with real and/or adopted children and grandchildren.

### 6) Conclusion

As discussed above, in the span of one's life, people experience changes in both social and natural environments. If in the past social environment was adapted to the natural environment, in modern times, the social change brought about by government policies is often rapid and its effect so strong that people are busy to fight with the change. Under such circumstances, people usually have no time or feel at loss as how to respond to the change in natural environment. This is why understanding the social dimension is essential to researching the natural environment.

# Population Change, Water Consumption and Environment in the Upper Heihe River Basin

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This article will reveal the formation process of population composition, today's water consumption pattern and environmental issues acknowledged by local people including government officials of Xiang level in the upper Heihe river basin, especially focusing on cases in the "uppermost area".

As usual, Heihe is discussed in 3 areas; upper, middle, lower. As for mainstream Heihe, "the upper Heihe river basin" covers the area upper than Yingluoxia gorge, where Heihe flows into the oasis area of Hexi corridor from Qilian mountain range, and "the lower Heihe river basin" covers the area lower than Zhenyixia gorge, where it flows into the desert area of Inner Mongolian Autonomous Area. This viewpoint coincides with that of people in Hexi corridor, that is, "the middle".

But from the viewpoint of "the upper", especially in socio-cultural context, we can distinguish two separate areas as to following criteria.

1. Topographic features: though this is not a socio-cultural phenomenon, but it can affect the pattern of land-use. As there is only one place where Heihe crosses Qilian mountain range from south to north, so at the south, Heihe and its major branch Babaohe flow along with the run of the mountains, shaping plains that can be utilized as farmland if altitude is relatively low. In contrast, at the northern slope of Qilian mountain range, Heihe and its branches flow in steep valleys and make little plain.
2. Administration: today divide of Qilian mountain range is the provincial border between Gansu and Qinghai. Historically, today's border was confirmed in the later 1950's. But anyway, difference in provincial attribution acts as a very important limiting factor in policy implementation or migration of peoples.
3. Ethnic groups and migrants: the lower and upper Heihe river basin is domicile of minority groups. In such areas of China, ethnic conflicts between minorities as natives and Han Chinese as newcomers are noticeable issues in usual. But as mentioned later, the situation is different in the western part of Qilian prefecture of Qinghai where a lot of immigrants were also minorities and it is even suspicious whether natives in a strict sense exist now.

Of course, the borders marked off by these criteria do not completely overlap. So it is still difficult to mark off "the uppermost area" by a clear-cut border from "the upper". But anyway, the western part of Qilian prefecture, which is equivalent to Yeniugou Xiang and Zamashi Xiang in an administrative context(1), can be said a central part of "the uppermost area" in that it fulfills all of the criteria and the riverhead of Heihe is located there.

As population change started from near zero in this area, it should have played a critical role in the changing process in mode of production and water consumption, which is the research target of anthropological group in Oasis Project. But as this area was once one of the main stages of border conflict between Gansu and Qinghai, none of local government has all of the materials concerned. So, reconstruction of population changing history in the area has rather significance.

Information sources are as cited below. Each of them has respective features.

1. Field research data in 2002-2004: in general, interviewees can retrace 3 generations at the most.
2. Statistics and materials collected from local governments: surviving materials are usually after 1980's, and reliability should be taken into consideration.
3. Published matters purchased in the area: on one hand, discourses concerning before 1949 are usually along the line with ethnicity, so it is difficult grasp spatial distribution. On the other hand, discourses concerning after 1949 are usually along the line with administrative units, although changes of administrative area are rarely mentioned.

In short, they are fragmentary respectively. Hereafter, total image of population change in the area will be shown as a consequence of integration and cross check by the author.

Establishment of Yeniugou and Zamashi Xiang was not so old. According to "Annals of Qilian prefecture", Zamashi xiang was established in September 1951, and Yeniugou was first established as a village of Zamashi in March 1953, promoted to Xiang in September 1958 (QXBW 1993:19-25, 50-51). Then, how was the situation of this area?

1. In early days of the liberation, rump of Guomindang army hid out in mountainous area. After their 3rd invasion failed in 1951, some of them refuge in Yeniugou. Fight with the rump continued until 1953 (QXBW 1993:411,550).
2. In 1945, 60 Haixi Mongolians immigrated to Yeniugou in response to ethnic conflict (QXBW 1993:503).
3. In 1937, Yugurs moved into Yeniugou and Huangzangsi for pastoralism (QXBW 1993:17)

4. Pests broke out 5 times 1928-38. Among them, at Zhaobishan(2) of Yeniugou, many sufferers died and few survivors emigrated to other places (QXBW 1993:481).
5. In 1929, Salars and Tus immigrated to Gezidong, Hedong, and Hexi for cultivation one after the other (QDBW 1999:336).
6. In 1929, 40 households of Gonghe Tibetans immigrated to north coast of Zamashi river. They started sedentary pastoralism and cultivation by permission of Alik Thousand Households (QXBW 1993:499)
7. In 1928, some Tibetan households of Alik Thousand Households (today's Arou Xiang) disfavored taxation and fled to Yeniugou, but were killed by Ma Bufang's soldiers (QXBW 1993:499).
8. In early days of Minguo, Gangcha Tibetans built a Buddhist temple in Youhulu of Yeniugou (today's southeastern part of Yeniugou Xiang), but was destroyed later in ethnic conflict during Minguo (QXBW 1993:510-511).
9. In 1901, 20 households of Tibetans from eastern part of Qinghai immigrated to Zamashi, got right of residence from an incarnation of Datong (QXBW 1993:499).
10. In 1895, Huis started immigration into Babao (today's prefectural center of Qilian) from Datong and Mengyuan (QXBW 1993:506).
11. In 1723, Mongolians built 2 Buddhist temples in babao (QXBW 1993:510).

From above information, we can know that the immigration, which brought about today's population composition in western part of Qilian prefecture, started only 100 years or so, and that among others Yeniugou was such a remotest place that stragglers and escapees fled to.

On the other hand, from the viewpoint of Sunan Yugur Autonomous Prefecture in Gansu Province, the reality looks a little different. In folk story of Yugurs, today's Yeniugou is mentioned as Bazidun (GB 1987:32-33). Sunan Yugur Autonomous Prefecture also regarded Bazidun as its domain at the time of its establishment. According to research reports of 1940's, we can infer that among subgroups of Yugurs, 15 households of Yanggejia out of total 47 households 229 people and around 200 people of Mantaibu lived in the southern slope of Qilian mountain range (Gao & He 2003:89,99-100; MZWD 2002:520).

But compared to 3136 people of Yeniugou Xiang in 2003, the population of Yugurs at that time was quite little. Additionally, as heartland of Mantaibu was located in northern part of today's Babao Xiang, so it is hard to imagine that all members of Mantaibu utilized Bazidun that is far westward from their heartland. Moreover, it is easy to find out a place name which originated in the language of former dweller. Taking it into consideration, change of the place name from Bazidun to Yeniugou might reflect weak presence of Yugurs in local society of the time.

The most important issue which affected the process of population change in the uppermost area was border conflict between Gansu and Qinghai through 1950's and large-scale migration attached to it. The prehistory and whole process of the issue was as following.

In 1929, Qinghai province was separated from Gansu, and the border was decided along the midrib of Qilian mountain range. But none of the province controlled the area effectively, and Ma military clique governed both provinces for a decade before establishment of P.R.C., so the border existed only in name (Gao & He 2003:166).

In 1954, the situation changed. At that year, National Graphic Publisher in Beijing published "Map of administrative district in P.R.C.", where the border between Gansu and Qinghai was set down on the midrib of Qilian mountain range. As it had legal force, Bazidun which was located at southern slope of Qilian mountain range was acknowledged as domain of Qinghai by the state (Gao & He 2003:150,157). At that time, as troop had just wiped out rump of Guomindang army, the authority of Qinghai gave silent approval of migration of pastoralists into Yeniugou area.

This border conflict was settled in August 1955. At that time, Gansu and Qinghai agreed that the border was decided along Heihe for the moment (Gao & He 2003:151). But in 1958, as a nuclear site was established at Haiyan prefecture that was adjacent to Qilian prefecture, 1752 immigrants flowed into Yeniugou and other Xiang in Qilian prefecture. This incident changed the number and composition of population Yeniugou drastically.

At the conference to adjust this issue held at Lanzhou in October 1958, deputation of Qinghai insisted the border of "Map of administrative district in P.R.C." (Gao & He 2003:151), so Gansu provincial government felt that withdrawal from the south slope of Qilian mountain area could not be avoided. Under such circumstances, Gansu province decided to displace whole population of Sunan Yugur Autonomous Prefecture to Huangcheng pasture which was located eastward from the original place (Gao & He 2003:151-152).

In the end, this plan was aborted by the order of Chinese Communist Party headquarters. But as to the uppermost area of Heihe, because Yugurs already moved to the north slope of Qilian mountain range, and people from other area had once immigrated into Yeniugou, the border was finally decided along the midrib of Qilian mountain range, confirming the actual situation. After that, border conflict did not happen, but even now, informants of Yugurs in Gansu part of the area argue that pastoralists from Qinghai part often cross the border for herding due to growth of population as a result of large-scale migration in late 1950's.

Although it is impossible to demonstrate detailed figure by respective Xiang as we have not gotten materials for such purposes, population of Qilian prefecture as a whole changed as following; 8023 (1st population census in 1953), 19140 (2nd population census in 1964), 36405 (3rd population census in 1982), 42392 (4th population census in 1990) (QXBW 1993:107; QDBW 1996:74). Annual growth rate of population is 8.25% (1953-64), 3.64% (1964-82), and 1.92% (1982-90) (GT ed. 1989:88).

On the other hand, population growth rate of China at large, except 1958-61 when influence of Great Leap Forward was extremely severe, in the low 20‰ in 1950's and the former half of 1970's, in the high 20‰- the low 30‰ in 1960's, below 15‰ after 1976 (GT 1989:88). Taking it into consideration that Qilian prefecture is classified as minority area where family planning policy was imposed modestly, population change after 3rd population census can be taken roughly as the result of natural increase. In contrast, population change between 1st and 2nd population census was dominated by radical social increase, and even between 2nd and 3rd impact of social increase may be assumable to some extent.

As to mode of production and patterns of water consumption, we can point out that those are almost alike in an area regardless of ethnicity, although we can find out some traits which can be recognized as ethnic marker or characteristics of some ethnic group. According to the field data of the author in 2004, in Zamashi, 3 informants of Hui, Han, and Tibet who all admitted that they themselves are immigrants from Babao, Mingle, Huarong answered as following; they are farmers cultivating wheat, qingke barley, crucifer, and oat, at the same time herding livestock (sheep, cattle, horse) in transhumant way. They irrigate 1-3 times (depending on rainfall) a year, each time for 1.5 hours per mu, and water livestock 1-2 times a day, recognizing that a sheep drinks 3kg and cattle drinks 15kg a day. Their cropping calendar is basically the same and they have no idea about amount of water for domestic use, and so on.

In Yeniugou, although they are pure pastoralists who don't cultivate a field other than very small-scale (1 mu or so) fodder field, their recognition about amount of water livestock drink and they themselves use for domestic use, are the same with people in Zamashi, too. 3 informants of Yugur, Hui, and Tibet all agreed that their way of pastoralism including seasonal migration pattern was basically the same in direction and time.

Their recognition of waster resource varies from place to place; people in Zamashi all feel that their water resource is affluent and not polluted. On the other hand, people in Yeniugou all feel that they have long been short of water resource although it is not polluted, as in their summer pasture there is no permanent onflow of mainstream Heihe and have to go up to mountain for water. Even in their winter pasture, they have to utilize ice from Heihe or a small spring.

Their thoughts on environmental change also vary according to the inhabited area, though they all feel the situation not catastrophic anyway. In Zamashi, their concern on environment is only "stop cultivation to revive forest (grassland)" policy, which was imposed in 2002 but stopped later, as it had a severe impact on peasants' life. In Yeniugou, its equivalent is improvement of grassland by grassland station, which accompanies enclosure of grassland for 3-5 years; in consequence amount of grassland pastoralists can utilize is on the decline.

Originally, Yeniugou is named after wild cattle (Yeniu) as a lot of them lived there; but they were put almost out of existence because of overhunting caused by starvation after Great Leap Forward. Besides, an informant pointed out decay of rainfall over recent 20-30 years, gradual increase of mice as use of mouse poison was prohibited, and increase of wolves as they are prohibited to hunt because of their status as protected animal. It is true that they feel their natural surroundings may be worsening, but if they emigrate anywhere, it is not because of natural factors but social factors such as remoteness or poor infrastructure.

In closing, what remains to be done in the future should be pointed out. First, a history of population change, water consumption and environment in the whole upper Heihe river basin must be written up; for this purpose, basic materials were obtained already. Second, a quantitative model of water consumption must be brought up; in doing it, some additional observational research especially for estimation of domestic water use may be required.

Notes

(1) For more detail, see (Ozaki ND).

(2) Zhaobishan is toda's Bianmacun village center in the eastern part of Yeniugou Xiang (QXBW 1993:52).

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# The Use and Change of Natural Resources in the Middle Reach of Heihe River

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This is a report of my fieldwork on changes of life and use of water resource. My site of investigation is Gaotai 高臺 county, the oasis area located in the middle of the Hexi 河西 Corridor.

The Gaotai county is located on the river banks of Heihe 黑河 River. It is a grain producing region with a relatively intensive use of land. It is a state-designated commercial grain production base, and it has also become a base for shipping vegetables from west to east. The north, west, and south parts of the county are desert. In order to increase grain production, the state has been encouraging peasants to expand into the desert. The government relocated large numbers of migrants to drill wells and reclaiming land, to transform the previously gobi wasteland into oasis.

1. The Heihe Drainage Area – Intensive Farming

The Heihe River banks of Gaotai county is an agricultural region that relies on irrigation. It averages 1200-1346 meters above the sea level, with fertile soil and abundant resources of heat and light. It occupies a key position in the east-west transportation line, with the Lanzhou-Xinjiang Railroad and the #312 State Highway running through it. Therefore, it is designated by the state as a major base for grain production. The river banks have excellent conditions, but it also has a large population that put restriction on raising production and income. In order to develop agriculture, people here are constantly seeking ways to intensify the use of land.

This region has a long history of wheat cultivation, and the traditional crop pattern was one harvest per year. The output per mu was about 130 kilogram during the 1960s. Since then, Gaotai county has been building up its agricultural infrastructure, constructing irrigation system and water channels, and lining them with trees. Beginning from the 1970s, the county reformed cultivation method to increase double cropping and alternate planting. The main patterns of alternate planting are wheat-corn, broad bean-corn, and beet-corn. The traditional crop pattern of one harvest per year is also replaced by twice or multiple harvests a year. These measures effectively increased output per mu and extended crop growing period to about 200 days per year. Since the 1980s, agricultural output increased dramatically with the spread of chemical fertilizer, pesticide, and mulch film. According to statistics, the output per mu in the river drainage region increased as follow:

137 kilogram 1963
210 kilogram in 1972
420 kilogram in 1983
556 kilogram in 1988
It is a four-fold increase in twenty years.

Chinese population grew rapidly in the 1960 and 1970s. It may be said that the Hexi

Corridor area made a great contribution to relieving the crisis caused by population pressure. However, the raise of grain production meant increased water consumption of water at the same time. Over use of water caused disappearance of river and drying up of lakes in the lower stream. A more counter-intuitive fact is that tree planting caused lowering of underground water table. According to local peasants, tree need more water than grain. One tree has the effect of a water pump.

Not only the lower stream, but also the middle stream of the Heihe River experienced problem of water usage. In the 1990s, the Heihe River entered drying up period. Each year, the river stopped flowing in the middle and lower stream between late summer and early fall and crops were threatened with the "strangling draught." According to local people, there were many springs on the river banks before the 1970s. People basically could rely on the spring water to secure irrigation and relief draught. But now pumping water from well has become an important way to fight draught and develop agriculture. Gaotai county drilled the first well in 1970 (40 meters) which began the practice of using underground water. In order to relief shortage of water, Gaotai county drilled many wells. When using river water for irrigation, underground water was also channeled to supplement river water and increase the water volume. The county realized the goal of "big increase of output when there is no rain, and big harvest when there is a big draught."

Since the 1980s, with the change of city people's diet, Gaotai county has also been adjusting its production structure. It quickly expanded the acreage for vegetables and fruits that can bring better financial return. The Heihe River bank area in particular has begun producing vegetable during off seasons by mainly relying on greenhouse. The development of greenhouses enabled the county to overcome the limitation of unfavorable land-people ratio in agricultural growth. This made it possible to achieve the historical transformation of using farmland all year long.

Gaotai county is located in the path of the Lanzhou-Xinjiang Railroad and the Number 312 State Highway. Such favorable geographic location allows it to ship its vegetables to various places, and it can hardly satisfy such demand. At the present, the county's greenhouses are developing rapidly and it has become a base for shipping vegetables from west to east. According to my fieldwork, the greenhouses completely rely on underground water. Peasants are not willing to use the river water, because water management of Heihe River is becoming stricter and the price for water is constantly rising. In order to gain freedom for using water, many people equipped the greenhouses with their own machine-pumped well. Currently, tens of thousands of wells in the river drainage area are pumping underground water around the year. Undoubtedly, this is going to greatly speed up the process of exhausting the water resource.

2 The Gobi area of Gaotai County– Land Reclamation

Gaotai county is largely surrounded by gobi desert. Starting from the 1950s, several times the government relocated migrants to the Hexi Corridor to explore the land. One of the methods employed to reclaim wasteland was setting up military colonies. The production and construction companies（建設兵團）of the People's Liberation Army

(PLA) established land reclamation district in the Hexi area. They opened fields and mines, ploughed grassland into farmland, and irrigated gobi desert into oasis. Currently, the oasis is still expanding.

In the 1980s, the government once again set up a group of migration bases. Luotuo cheng 駱駝城 township is one of them. The township presently has eleven administrative villages. Its population totals over ten thousand, and they are all migrants. Migration development is essentially exploration of water resources. The government aids migrants by drilling wells for them for free. Even the settlement sites are named after the numerical order of the wells: Number 1 Settlement, Number 2 Settlement, etc… The population also expanded with networks of relatives and friends. Through transformation of the last twenty years, the previous wasteland has become high-output fields. Now, there is more and more land exploration in Luotuo cheng township. Besides peasants and enterprises, even some administrative units have joined the ranks of land reclamation.

Bailongjiang 白龍江 Bureau of Forestry, one of the ten big forestry enterprises in the nation, organized over one thousand and three hundred workers and their family members to work on reclamation. It opened up thirty thousand mu of land in Luotuo cheng township, and set up a grape-growing base and wine brewery.

The tens of thousand mu of farmland in Luotuo cheng township are completely relying on underground water. Within its territory, there are over three hundred pump-wells that are more than 100 meters deep. Due to the increase of migrants and the expansion of farmland, underground water resource has been overly consumed. According to my investigation, the water table in this area is more than 20 meters lower than it was before such development.

3. Water-Save Farming -- Exploration of Water Resource

In recent years, ecological problem in the Heihe River area is becoming increasingly more serious. It is particularly so in Eznee(額吉納)in the lower stream area, where lakes are drying up and sand storms blow frequently. For protecting the ecological condition in the lower stream, currently the middle stream is practicing water-save farming. The government invested large sums to construct or rebuild the main water channels and the large and small branches for the purpose of reducing the amount of water lost in the process of irrigation, and to ensure diverting water to the lower stream. Recently, each year from May to August, about 15 days per month water is diverted to the lower stream. During those days, the government forbids peasants in the middle stream to use water in the Heihe River. It closes outlets in the river so that water is concentrated to flow down to the lower stream. Even though Gaotai is a major agricultural county, it has observed the state's water-channeling quota and accomplished the task of diverting river water every year. Generally speaking, an agricultural region that relies on irrigation must make sacrifice in order to save water. However, I have discovered in the fieldwork that the local people very much welcome the water-saving project. This is because "when there is policy from above, there is strategy from below." People here are taking advantage of the historical chance provided by the"water-saving project"to build up infrastructure with the construction of V-shaped water channel. For the local people, saving water means to rationalize water use in the irrigation process. It has always been the people's desire to build matching set of main water channels and branches, to improve irrigation method, to use water more effectively, and to solve the problem of insufficient water volume at the water channel terminals. When they are not allowed to use the river water, they use underground water. Especially in the land reclamation areas settled by migrants, well-drilling and matching construction of water channels has greatly encouraged the pace of reclamation. News media is also praising "the Heihe River water-saving project have realized the dream of those who reclaiming land in the gobi desert." Currently, the various water channels are extending further. Migrants are pouring water from well into the channels to speed up the pace of irrigation. We may say that the Heihe River water-saving project will cause further expansion of the oasis. The water channel construction in the water-saving project has already become another threat to the ecological condition of the Heihe River area.

# Environmental and social changes of the past fifty years in the Ejina Oasis of the Heihe River Basin

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## 1. Introduction

The purpose of this paper is to provide an analysis about environmental and social changes of the past fifty years in the Ejina Oasis of the Heihe River Basin. I focus on the process of how the recent Chinese policy influenced to ecological resources.

## 2. The present Ejina Oasis

Ejina banner has little rain, only 39mm per year, and is located in the most arid district in China (Fig.1). However, because Ejina banner is located in a relatively lowland area, snowfall and rainfall in the Qilian mountains flow into Ejina banner, forming the Heihe River (Fig.2). Ejina banner is located in the lower reaches of the Heihe River Basin. Therefore, the landscape of Ejina consists of meadows, firewood, bush and shelter belts along a river flowing through the Gobi desert (Fig.3). The Heihe River forms an oasis in Ejina banner.

The oasis, formed in the arid area under little rain, has been a point of North-South traffic importance (Momiyama, 1999:41). Until today, this geographic importance has not changed at all. Ejina banner now also contains a missile base and a rocket-launching base (Erjiniqizhibianjiweiyuanhui, 1998:655-660).

The total area of Ejina banner is about 115,000 km$^2$, and is equal to one third of that of Japan. On the other hand, the population of Ejina banner is only about 16,694 people in 2003, so the population density is only 0.15 person per km$^2$. Most of the population is concentrated in the basin.

The chief industries in Ejina banner are pastoralism and agriculture (Fig 4.). Pastoral people had practiced 'Oasis Nomadism', using the abundant ecological resources of the river and moving within the Ejina Oasis (Konagaya, 2004:5). It is not until 1956 that Agriculture in Ejina only started. Farmland is possible only along a river because agriculture requires irrigation using water of the river and underground water (Fig 4.).

## 3. Environmental changes in the past fifty years

The most significant environmental change in the Ejina Oasis over the last fifty years is a decrease in the amount of water flowing downstream.

Figure 5 shows a comparison of the amounts of water flowing in the upper, middle and lower reaches of the Heihe River Basin. The amount of water in the upper reaches has been relatively stable. However, the amount of water in the middle reaches has decreased sharply, especially during the 1990s. This is because a large amount of water has been taken for irrigation by dams in the river's middle reaches (Yang, 2002). The total area of irrigated farmland in the middle reaches of the river has increased more than two times since 1949, growing from 110-120 thousand hectares to 270 thousand today (Yang, 2002:30). Accompanying the increase of irrigated farmland was a rapid increase in population. The population of the middle area reached 1,760,000 in 1995, accounting for 97 percent of the population of the entire river basin, and equal to 112 times that of Ejina banner (Fan et al, 2001:13).

As the amount of water taken from the river increased, the amount of water flowing downstream has decreased sharply (Yang, 2002:52-53). Annual precipitation has also decreased (Konagaya, 2005). For these reasons, the river has often dried up. Moreover, one of the two big lakes located at the terminus of the river disappeared in 1961, and the other became smaller year by year until it disappeared in 1992 (Yang, 2002:7). However, the second lake appeared again in 2003, though at a small scale.

## 4. Social changes in the past fifty years

Significant social changes in the last fifty years are the People's Communes in 1958-1983, the Cultural Revolution in 1966-1976 and privatization of livestock and land in 1983.

Ten years after the establishment of the Republic of China in 1949, the People's Communes started, and livestock became common property of the communes (Erjiniqizhibianjiweiyuanhui, 1998:175). A quarter century after the start of the People's Communes, they were dissolved and the Household Responsibility System started in 1983. This was accompanied by privatization of livestock and land. With privatization of livestock, market prices have influenced the pastoral economy and life (Kodama, 2003). Privatization of land has led pastoral people to reduce mobility and has promoted settlement, except in some Gobi districts where land was not privatized.

After about twenty years from the start of the Household Responsibility System, the Chinese government applied its 'Ecological Migration' policy to Ejina banner in 2002. The 'Ecological Migration' policy forces pastoral people to migrate from the oasis to outside, for the purpose of preserving the oasis (Kodama, 2005). The oasis will be enclosed by fences and livestock grazing will be forbidden. This policy covers about 1,500 people, almost a tenth of the population of Ejina banner.

Most ecological migrants will engage in static livestock farming; the migrants feed stock feed to sheep, goats and cattle in a shed, cultivating the stock feed by themselves. For this purpose, the government plan provides them with fields covering all the farmland of Ejina banner in 2001 and deepwater wells with electric pumps. It has been pointed out that the 'Ecological Migration' policy has two risks: the decrease in income of ecological migrants, and exhaustion of underground water (Kodama, 2005).

## 5. Population changes

Although the amount of water flowing downstream has decreased, the population of Ejina banner has increased more than eight times (Fig.6.).

## 6. Changes in agricultural production

Why has the population increased in Ejina banner despite a decrease in the amount of river water?

Figure 7 shows changes in the area of farmland in Ejina banner. The total area of farmland rapidly increased until the 1970s, reaching 150 times that of the 1950s. More specifically, it was only 27 hectares in 1956, and after twenty years it increased to 3,500 hectares in 1976. The total area of farmland started to decrease in the 1980s, and it dropped to around 1,900 hectares. This means 1,600 hectares of farmland were abandoned. However, this trend reversed and the area of farmland began to increase again in 2002.

The yield per unit area has been relatively steady, even though the amount of water flowing downstream has decreased (Fig. 8.). This is because the use of underground water has spread. In the 1960s, when agriculture in the region started rapidly, people began to use open wells, and in the 1970s they started drilling deepwater wells (Erjiniqizhibianjiweiyuanhui, 1998:259).

Among these changes, the plants cultivated also changed. In the People's Communes, pastoral people had cultivated wheat for food. With the privatization of land in 1983, they started to cultivate corn and sorghum for livestock feed. In the 1990s, cotton and melons were cultivated for sale. It is said that income from selling cotton reaches 10,000-15, 000 yuan per hectare.

Moreover, the increase in cultivation of these cash crops caused an increase in the total area of farmland since 2002, when the 'Ecological Migration' policy began.

Because ecological migrants can't earn enough income from livestock farming, they have to obtain income from other sources, mainly cash crops. Many pastoral people are not good at farming, so they rent the land to people who come from other districts, mainly Han Chinese. As a result, the price of farmland has increased more than five times in only two years, and farmland for rent is rapidly being reclaimed on private land.

The demand for water resources is rising with the increase in farmland under the 'Ecological Migration' policy. Water resources have to depend on underground water because there is little hope of increasing the amount of water flowing downstream from the Heihe River.

In conclusion, the increase in population is supported by the increase in agricultural production. And this increase of agricultural production depends on the underground water.

## 7. Changes in pastoral production

Under a decrease in the amount of water flowing downstream and expansion of agricultural production, how has pastoral production, a main industry of Ejina banner, changed?

Figure 9 shows the changes in livestock totals for the past fifty years in Ejina banner. The number of livestock increased from 96,000 in the 1950's to 155,000 in the 1980's, reaching one and a half times that of 1950s. However, the number of livestock has been decreasing from the 1990's until now, especially since 2001. The total number of livestock in 2003 was almost the same as in 1956.

## 8. The past fifty years in Ejina

Major changes of the past fifty years in the Ejina Oasis are a desertification caused by a decrease in the amount of water in the river and the agricultural development of the oasis by an increased population. The area of the oasis has decreased about eight percent since the middle of the 1980's (Yang, 2002:12). The percentage of the total area in Ejina banner suffering desertification has increased 32 percent over twenty years since the 1980s (Yang, 2002:10). According to a herdsman in his sixties who had once moved seasonally near a lake, a well ten meters deep which could provide drinking water for three hundreds camels every day had dried up because water from the river stopped emptying into it. Therefore, while grasses tall enough to hide a camel were growing luxuriantly until the 1960s, they barely cover the ground now. Because of desertification, the oasis has become one origin of sand storms

(Sugimoto et al, 2002).

Nevertheless, the exploitative development of the oasis and intensive use of underground water have been rapid since 2002 because of the 'Ecological Migration' policy based on agriculture.

The struggle for water in Ejina banner isn't obvious, because development of water resources is undergoing on private land. But the use of water resources there is very exploitative.

## 9. Conclusion

In conclusion, the privatization of land does not stop but rather promotes exploitative use of ecological resources, and the 'Ecological Migration' policy carries with it the danger of making desertification worse.

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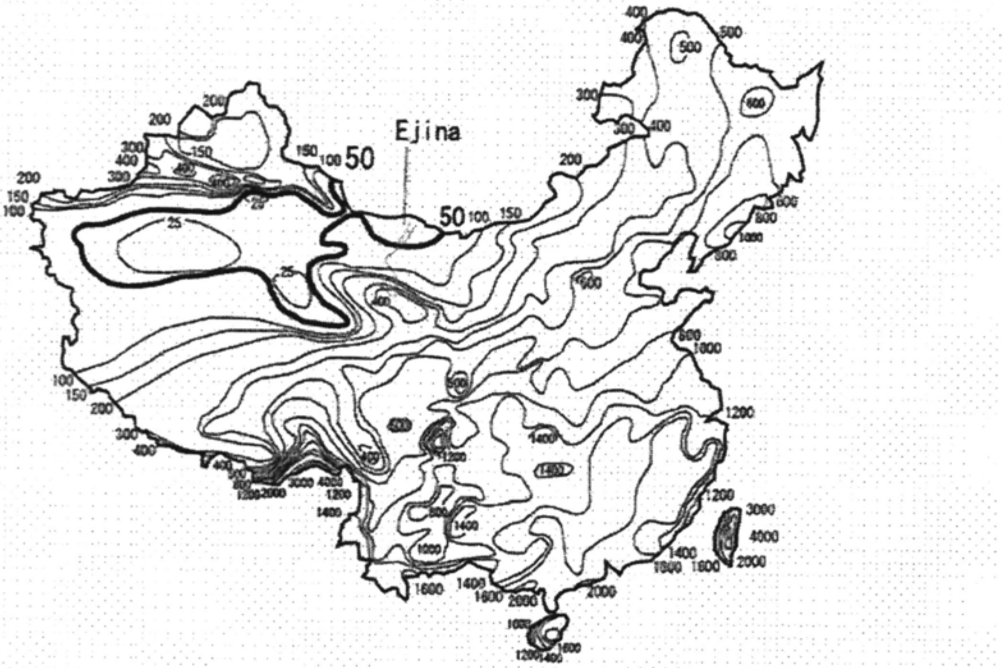



Fig. 1. Anuual Precipitaion Amouts in China

(Editorial Committee for the Climatologcal Atlas of the People's Republic of China, 2002:49)

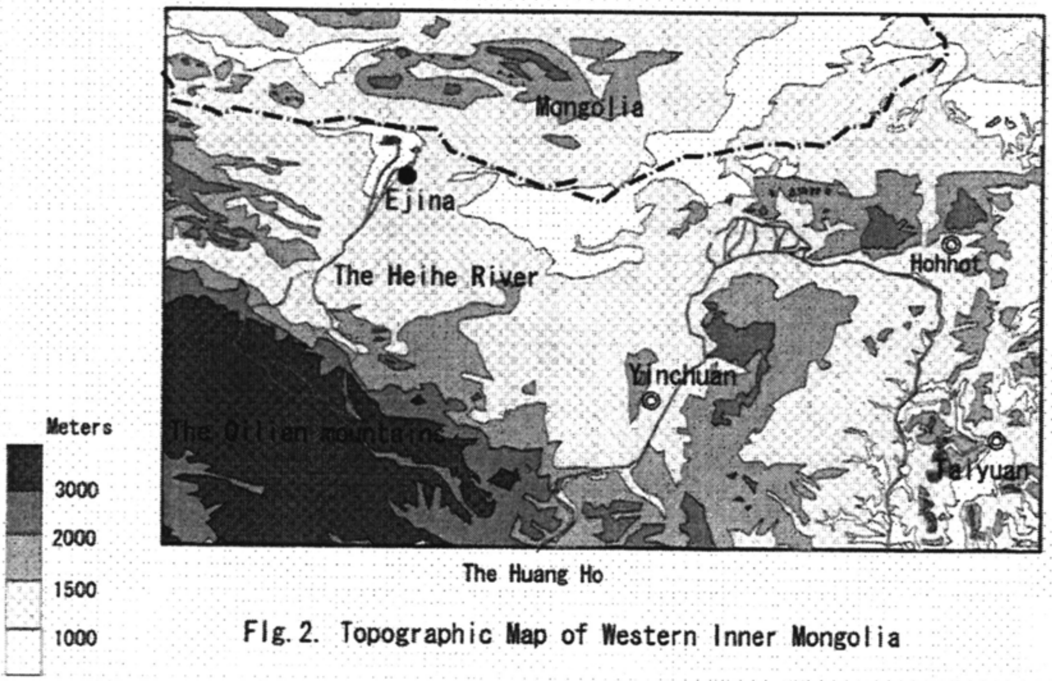



Fig. 2. Topographic Map of Western Inner Mongolia

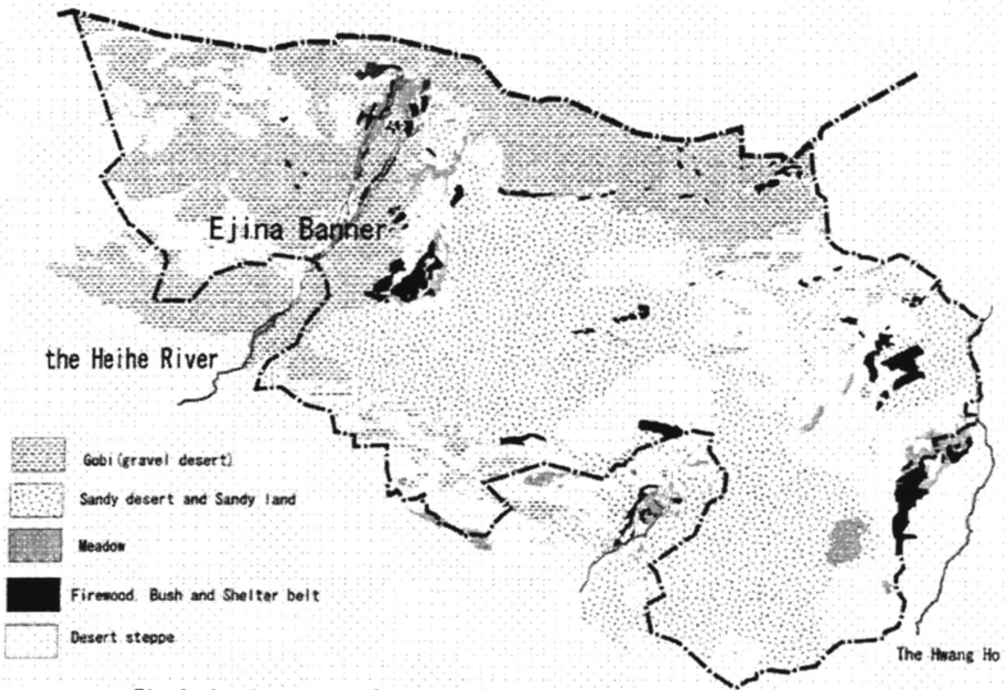



Fig. 3. Land-use map of Alashan league, China

(Editorial Committee for 1 : 1000000 Land-use Map of China, 1990)

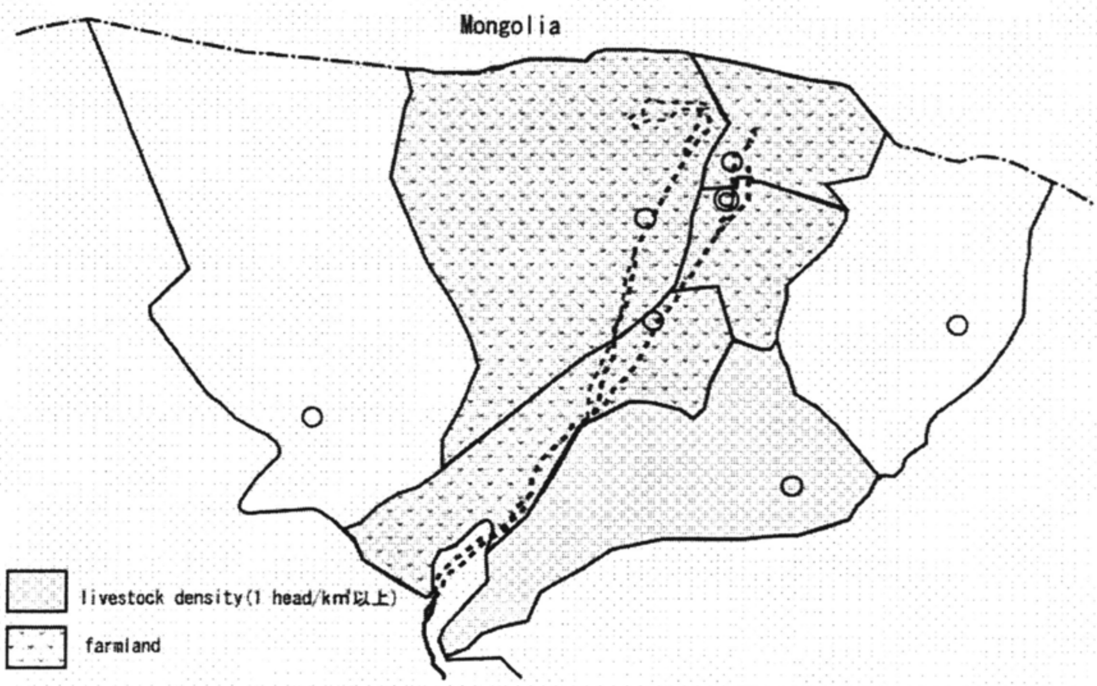



Fig. 4. Farmland and livestock distribution map of Ejina

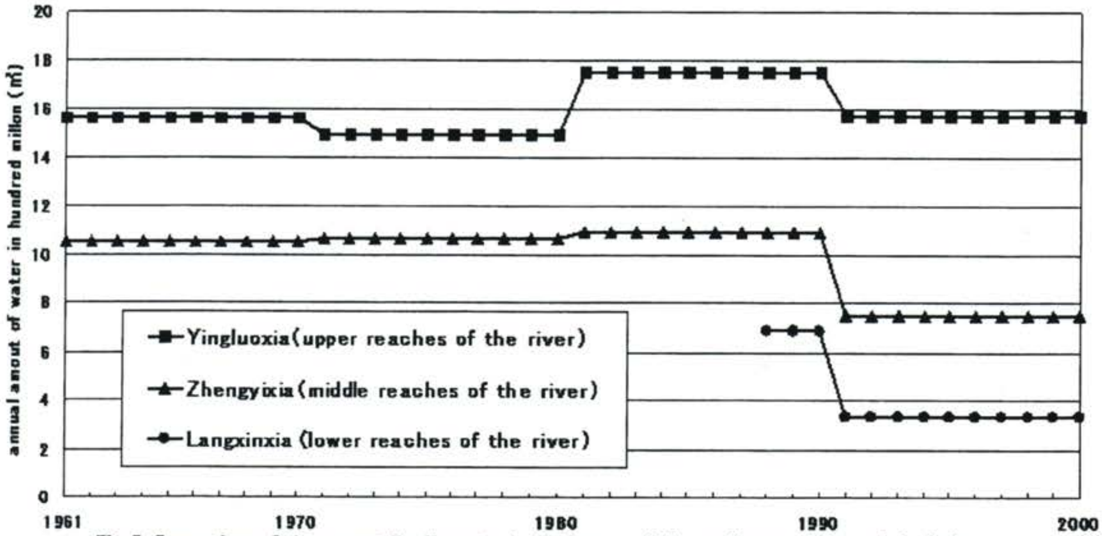
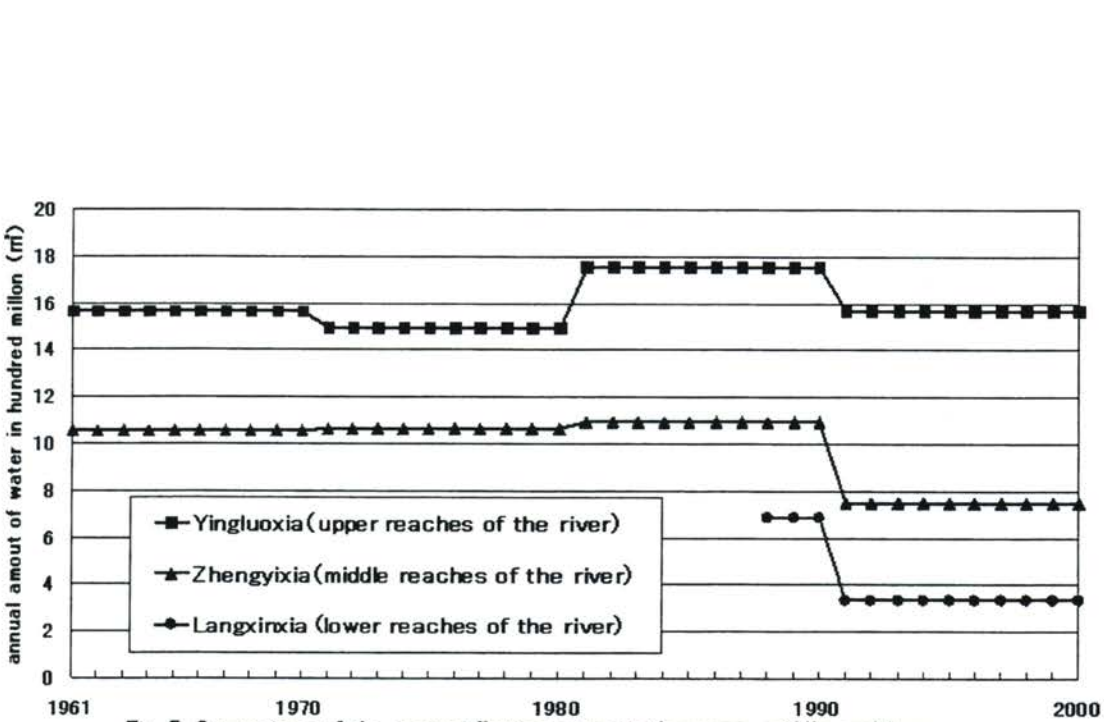



Fig. 5. Comparison of the amount flowing water in the upper, middle, and lower reaches of the Heihe River Basin, 1961-2000 (Yang, 2002:53-54)

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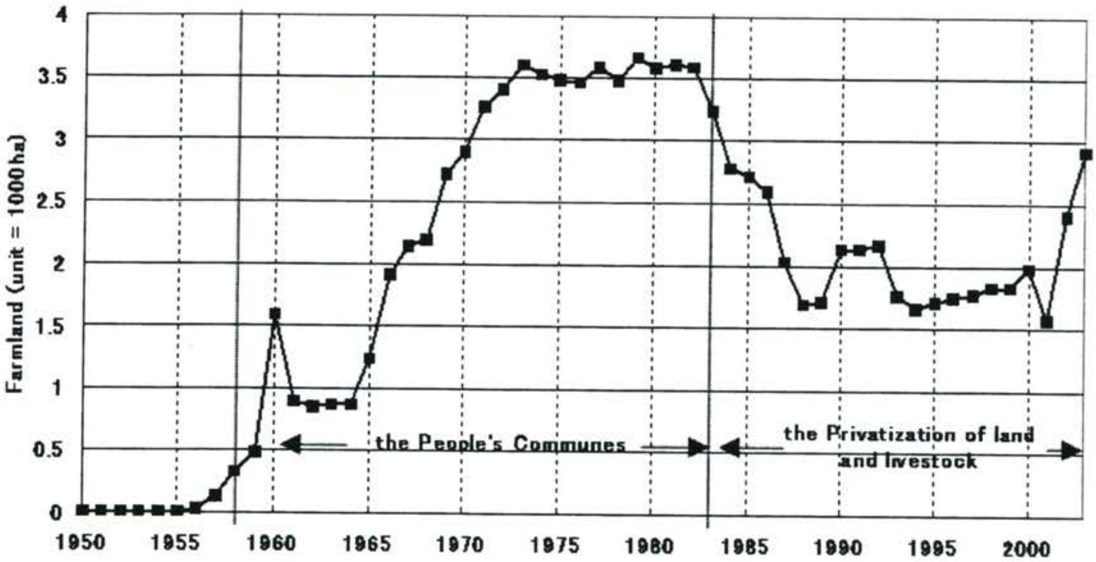


Fig. 7. Total cultivated acreage in Ejina banner, 1950-2003

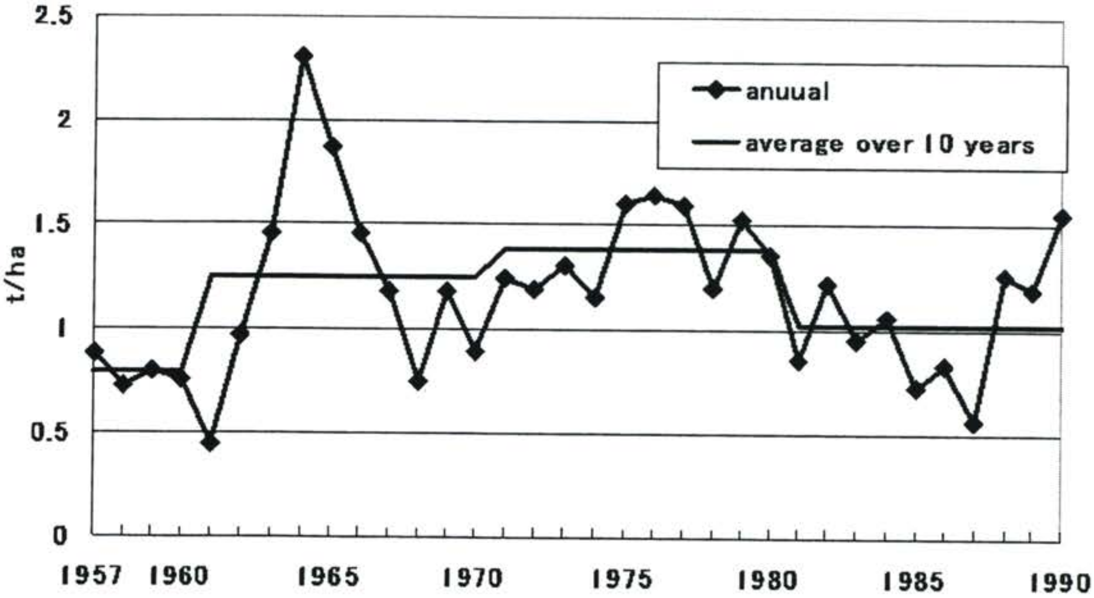


Fig. 8. Yield per Hectare of Ejina banner, 1957-1990
(Erjinaqizhibianjiweiyuanhui, 1998:257-258)

Fig. 9. Livestock totals in Ejina banner, 1950-2000

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## Research Program:

Historical validation of "sustainability" and "development" through the interactions of human activity and changes in the global environment
研究プログラム〔歴史時間軸〕
「地球環境変化と人間活動の相互作用による[持続性]と[発展性]の歴史的検証」

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Historical evolution of the adaptability in an oasis region to water resource changes
研究プロジェクト
「水資源変動負荷に対するオアシス地域の適応力評価とその歴史的変遷」

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